Simulating speed in language: contributions from vision, audition and action.

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Declaration

I, Laura Jane Speed, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Signature

Abstract

Embodied theories propose that understanding meaning in language requires the mental simulation of entities being referred to. These mental simulations would make use of the same modality-specific systems involved in perceiving and acting upon such entities in the world, grounding language in the real world. However, embodied theories are currently underspecified in terms of how much information from an event is contained in mental simulations, and what features of experience are included.

The thesis addresses comprehension of language that describes speed of events. Investigating speed allows embodied theories to be extended to a more complex feature of events. Further, speed is a fine-grained feature and thus testing an embodied theory of speed will reveal whether or not mental simulations include the fine details of real-world experience. Within the thesis four main methods of investigation were used, assessing simulation of speed with different types of speed language under different conditions: behavioural testing combining speed in language with speed in perception and action, eye-tracking investigating whether eye-movements to a visual scene are affected by speed in sentences, a psychophysics paradigm assessing whether speed in language affects visual perception processes, and finally, as a crucial test of embodiment, whether or not Parkinson's patients, who have difficulty moving speedily, also have problems with comprehension of speed language.

The main findings of the thesis are that: (1) speed, a fine-grained and abstract dimension, is simulated during comprehension, (2) simulations are dynamic and context-dependent, and (3) simulations of speed are specific to biological motion and can encode specific effectors used in an action.

These results help to specify current embodied theories in terms of what the nature of simulations are and what factors they are sensitive to, in addition to broadly

providing support for the sharing of cognitive/neural processes between language, action and perception.

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Chapter 1 Introduction

Understanding the meaning of words and sentences is crucial to our ability to function in the world. To do so we must reliably map the arbitrary form of a spoken or written word to the corresponding concept whether it is present in the environment, tangible or merely imagined (Meteyard, Cuadrado, Bahrami, and Vigliocco 2012, p.2). These mappings are combined to form a wider representation in the case of sentences. This thesis addresses how humans manage to do this, specifically focusing on concepts related to speed. In this introductory chapter I describe two main approaches to understanding meaning in language (also referred to as 'semantics'): symbolic and embodied theories. Symbolic theories typically describe meaning in terms of abstract holistic symbols (words). Current versions, distributional semantic theories, assume that semantic representations arise from language use: out of the statistical patterns that exist amongst words in a language. These theories focus only upon linguistic data, using statistical techniques to describe words' meanings in terms of their distributions across different linguistic contexts (e.g. Burgess & Lund, 1997; Landauer & Dumais 1997; Griffiths, Steyvers & Tenenbaum, 2007). Embodied theories, current versions of featural theories of semantics, instead propose that understanding the meaning of words requires the mental simulation of entities being referred to (e.g. Barsalou, 1999a; Stanfield & Zwaan, 2001; Glenberg & Kaschak, 2002). These mental simulations make use of the same modality-specific systems involved in perceiving and acting upon entities in the world, such as perception and action systems. Thus they ground language in the real world and move away from abstract, symbolic representations of word meaning. The investigation presented in this thesis addresses the comprehension of speed language from an embodied perspective, thus the latter part of the chapter describes embodied theories in more detail.

To begin the chapter, I will introduce the 'symbolic versus embodied' debate from a general cognitive science perspective, later moving on to discuss how each approach can be used to describe semantic representation and processing more specifically.

1.1 The overarching debate: symbolic vs. embodied approaches to cognitive science

1.1.1 Symbolic cognition

During the cognitive revolution around the middle of the twentieth century, much of the work in cognitive science adopted a symbol processing view that neglected the role of perception (e.g. Newell & Simon, 1961; Fodor, 1975). Here, cognition proceeds via algorithmic processes on symbolic representations. This has since been the 'standard' view of cognitive science until recently. The 'cognition-as-symbol manipulation' framework was highly influenced by major developments outside of cognitive science such as logic, statistics and computer science, themselves heavily influenced by the development of the computer in the 1950s and 1960s (Barsalou, 1999a). Symbolic approaches (e.g. Newell & Simon, 1961; Fodor, 1975) focus on the architecture of a system, the processes that operate on symbols within a system and how the symbols are related to each other, rather than the content of the symbols, which are thought to be the same regardless of what they are symbolizing. Cognitive processes and perceptual processes here are completely separate systems operating using separate principles. For symbols to represent referents, sensory and motor information taken from perceptual input must be transduced into a different representational format, containing no perceptual information (see Figure 1-1a).

The symbols postulated in such approaches are abstract, amodal and arbitrary: they are empty of content, bear no relationship to the perceptual states they are transduced from and there is no systematic link between a particular symbol and its referent. Consider the number "4" as an analogy. There is no intuitive reason for the numeral "4" to be used to refer to the concept "four", and it could just as easily have been referred to using "5" or any other numeral. Cognitive processing is thought to arise from the manipulation of such arbitrary symbols within the system.

For the standard cognitive scientist, the study of cognition involves an analysis of the computational processes occurring within the black box of the mind only: the boundaries of cognition are drawn at the points of interface with the world (Shapiro, 2011, p. 26). Even at the later part of the twentieth century this was the predominant view: “[t]he central focus of psychology concerns the information processing that intervenes between sensory inputs and motor outputs” (Holyoak, 1999).

1.1.1.1 Problems for the symbolic view

Despite the popularity of these approaches they face many problems. First, there is little evidence that abstract symbols exist. Similarly, there is no satisfactory description or evidence of the transduction process; a fully developed theory is missing. Anderson (1978) argues that symbolic views are too powerful since they can explain all phenomena post-hoc, but conversely, do not make any a priori predictions. They are therefore unfalsifiable and not parsimonious.

A major argument against symbolic views, which embodied theories particularly build upon, has been described as the ‘symbol-grounding problem' (Harnard, 1990). If cognition works via the manipulation of abstract symbols, which contain no information related to their referent in the world, then how does understanding proceed? This problem is well explicated in the famous thought experiment “the Chinese room” (Searle, 1984). In the Chinese room, an individual that is completely ignorant to the Chinese language receives messages written in Chinese posted into the room. It is their job to post the correct response to this message, in Chinese, out of the room. Of course, the individual has no idea what the message says or how to respond because they do not know any Chinese, but they have been given a large book containing instructions of how to correctly manipulate the incoming Chinese symbols to form the correct combination of Chinese symbols to send back out of the room. To an outsider, they simply see a message being sent into the room and a correct response being sent out of the room. Thus the person inside the room has the ability to correctly process the Chinese symbols and produce the correct output, but could you say that this person understands the meaning of the symbols and their message? This is precisely the type of operations proposed in traditional cognitive approaches.

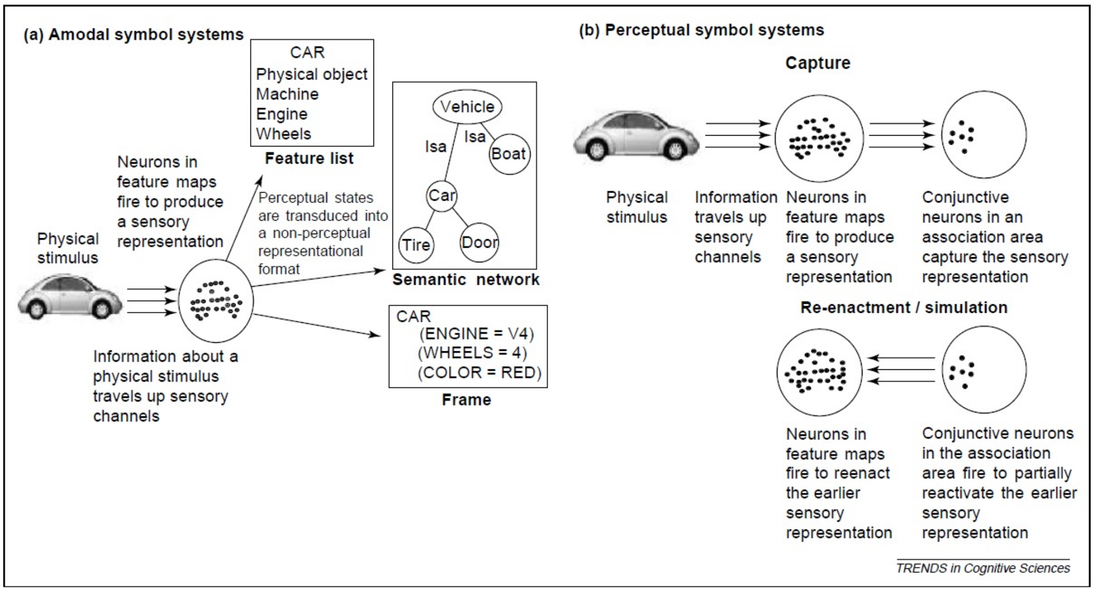


Figure 1-1. Amodal vs. perceptual symbols. Taken from Barsalou, Simmons, Barbey and Wilson (2003) (a) In amodal symbol systems neural representations from vision are transduced into an amodal representation such as a frame, semantic network or feature list. These amodal representations are used during word understanding. (b) In perceptual symbol systems neural representations from vision are partially captured by conjunctive neurons, which are later activated during word comprehension to re-enact the earlier state.

1.1.2 Embodiment

Embodied cognition is largely seen as a reaction to this ‘standard’ cognitive science approach as viewing cognition as the manipulation of symbols, and instead views cognition as the manipulation of sensory and motor information, extracted from real-world experience. Embodied cognition emphasizes the role of the body and the environment in cognitive processes: cognition emerges from interaction with the environment (Thelen, Schoner, Scheier & Smith, 2001). Theories of embodiment vary in terms of specific details, but in general all types of embodiment reject the standard view that meaning is wholly composed of abstract symbols.

Although work on embodied theories has been very prolific over the past ten years or so, it is to some extent still better seen as a “*research program* rather than a well-defined theory" (Shapiro, 2011, p.2). Shapiro (2011, p.2) points out that embodied approaches still have "roughly defined theoretical commitments" and few "uniform methodological practices". Since embodiment at present appears to be "poorly unified" (Shapiro, p.3, 2011) it may be more helpful for separate approaches to be differentiated rather than for all to sit under the same term. In response to the large amount of diversity in the claims made by embodied theorists Wilson (2002) sees it important to distinguish six different versions of embodiment. Table 1-1 outlines these six different versions.

In comparison to symbolic theories, strengths of embodied approaches are that they account for the fact that cognition takes place in specific environments for specific purposes and can be influenced by objects within that environment. Cognition is no longer hidden within the black box of the mind but extends out into the body and its environment. By assigning a role to the body and its interactions with the environment, embodied theories solve the 'grounding problem' (Harnard, 1990), linking the processes that make up cognition with physical referents in the world.

1.2 The symbolic vs. embodied debate applied to semantic representations

Before describing symbolic and embodied theories from a semantic view, I will first highlight some key issues that need to be considered in relation to all theories of meaning in language. The first addresses how conceptual information is related to semantic information. Various theories differ in how separable, if at all, the two types of information are. The second issue focuses on how words from different domains are related to each other, specifically whether theories posit the structure or the content of semantic representation as important factors in determining different domains.

1.2.1 How is conceptual information linked to semantic information?

The fundamental goal of language is to talk about and refer to things in the world such as objects, events and feelings. Thus, there must be a strong mapping between conceptual knowledge (the knowledge used to categorize and understand the world) and language. Since people begin life exploring and learning about the world, with language developing later, conceptual knowledge ultimately develops before language.

One important issue then is how words are related to conceptual knowledge. Should word meanings and concepts be considered interchangeable? If not, what type of mapping should be posited between the two? The way this relationship is described has many important implications, for example, to what extent there is translation equivalency across languages or how the language a person speaks affects the way they think (e.g. Boroditsky, 2001). There must exist at least a tight mapping between concepts and words: it is now clear that information beyond word meaning is activated when understanding words, such as motor information (Hauk, Johnsrude and Pulvermüller, 2004; Tettamanti et al., 2005). Because of this tight link, research into word meaning must ultimately tap into conceptual knowledge as well. Thus, one may question the need to distinguish between the two.

One argument for conceptual knowledge and word meaning to be thought of interchangeably is that many robust phenomena have been found to affect both concepts and word meaning. If the same factors affect them and they behave similarly, then they must be closely linked, if not interchangeable. For example, feature type, feature correlations and distinguishing features have been shown to explain both category-specific deficits in categorization of concepts (McRae & Cree, 2002; McRae, de Sa & Seidenberg, 1997; Gonnerman, Andersen, Devlin, Kemper & Seidenberg, 1997) and semantic priming effects for words (McRae & Boisvert, 1998). Because characteristics of conceptual features seem to have comparable effects it would be parsimonious to consider conceptual representations the same as word meaning.

However, there are reasons to suggest that there is not a one-to-one mapping between the two. First, it may be obvious that there are far more concepts than words. Murphy (2002) points out how there are often well-known actions or situations that are not lexicalized, such as "the actions of two people maneuvering for one armrest in a movie theatre or airplane seat" (Hall, 1984). Conversely, one can express the same meaning differently in different languages or even in the same language (take synonyms such as "*buy*" and "*purchase*" for example) and one word can be used to refer to multiple related meanings (i.e. polysemy) and so refers to a set of concepts instead of a single concept.

The relationship between words in a single language and concepts is therefore not so straightforward. This matter is further complicated when looking at cross-linguistic differences in the way that conceptual knowledge and linguistic representations are linked. It is generally assumed in cognitive psychology that the conceptual structure of humans is constant across all cultures and that there is a close correspondence between conceptual structure and the semantic structure present in languages. Yet despite this, there appear to be many differences across languages in terms of how conceptual information is mapped onto linguistic structures. For instance, although both English speakers and Italian speakers use different words to denote the two body parts "*foot*" and "*leg*", Japanese speakers use the same word "*ashi*" to describe both. One could hardly argue that conceptually, Japanese speakers do not know the difference between one's foot and one's leg.

The idea that different semantic structures could lead to differences in conceptual structure is referred to as the "linguistic relativity hypothesis" (Whorf, 1956). The strongest version of this hypothesis proposes a strict mapping: any semantic differences determine differences in conceptual representation. Weaker versions instead posit that linguistic differences can affect or shape conceptual representations, and specifically during verbal tasks (e.g. "thinking for speaking", Slobin 1996). For example, a wealth of research has shown that differences in the way that colour is lexicalised affects the way that colours are perceived (Gilbert, Regier, Kay & Ivry, 2006) and categorized (Kay & Kempton, 1984) but only for tasks that require verbal processes. That cross-linguistic variation is only observed, or at least is stronger, in verbal tasks, not for cognition more generally, suggests that word meaning and conceptual meaning can be distinct.

The existence of concepts without corresponding words, the ways that different languages carve up conceptual space into lexical forms, and the observation that language-specific effects on meaning are limited to tasks in which language is employed, all point toward a distinction between conceptual and semantic representations. Thus, word meanings and conceptual meaning should be thought of separately. Allowing for an intermediate level that binds conceptual information with linguistic information, such as syntax and phonology, into a lexical semantic representation, as in the FUSS model (Vigliocco, Vinson, Lewis & Garrett, 2004), can account for the differences observed across languages.

1.2.2 Are words from different domains represented in the same way?

The vast majority of research investigating meaning in language has focused on the study of concrete nouns. The past decade has seen increasing research into the representation of actions and a beginning of interest in the representation of abstract concepts. Across these domains, a critical question is whether the same overarching principles can be used, or whether, instead organisational principles must differ.

A fundamental difference between objects and actions is that objects can be thought of in isolation, as discrete entities, but actions are more complex, describing relations among multiple participants (Vigliocco, Vinson, Druks, Barber & Cappa, 2011). Connected to this are temporal differences: actions tend to be dynamic and have a particular duration, objects on the other hand are stable and tend to have long-term states. Related to the temporal domain is motion: compared to objects that are static, action occurs through time and space and must involve some representation of motion (Kable, Lease-Spellmeyer & Chatterjee, 2002).

Because of the stable nature of objects, the meanings of nouns tend to be relatively fixed. The meanings of verbs however are less constrained and often more polysemous. For example, in Wordnet 3.0 (Princeton University, http://wordnet.princeton.edul), a large online lexical database, verbs are given an average polysemy value of 2.17 whereas nouns are given 1.24. This means that on average, verbs have more senses associated with their meaning than do nouns. For example, the verb "*take*" could be used to describe many different acts such as a physical action resulting in some change of state: "*take an apple from the bowl*"; an action resulting in no change: "*take a look*"; or even something more abstract like an event of a certain duration "*take a break*".

These differences could underscore different representational principles for object-nouns and action-verbs, however, they do not necessarily preclude a semantic system in which objects and actions are represented in the same manner and differences in organisation come about because of differences in the content of the representations. An example of such a system is described by Vigliocco et al (2004) in their statistical model: the FUSS model. The model assumes two levels to semantic representation: one containing conceptual information and one lexico-semantic information. Word meanings are grounded in conceptual feature representations by combining conceptual features with other linguistic information such as syntax and phonology. Lexico-semantic space is organized according to featural properties, such as shared and correlated features. Importantly, the representations for action words and objects are modelled in the same lexico-semantic space, using the same computational principles. Differences between the two word types emerge from differences in the featural properties of the two domains, without requiring different principles of organisation.

Moving from comparing the domains of concrete objects and actions to comparing concrete to abstract words, here there is a much stronger case for assuming different content as well as different organisational principles. It is well established that processing abstract words takes longer than processing concrete words (the "concreteness effect"). A long-standing account of the concreteness effect comes from Paivio's dual coding theory (Paivio, 1971, 1986, 2007). Under this view two separate systems contribute to word meaning: a word-based system and an image-based system. Whereas concrete words use both word-based and image-based information (with greater reliance on the latter), abstract words rely solely on word-based information. The concreteness effect would occur because concrete words use two systems instead of one. Thus, concrete words would have richer semantic representations and they would be represented in a qualitatively different way than abstract words.

Alternative views, however, do not require multiple representational systems to account for the concreteness effect, such as the context availability theory (Schwanenflugel & Shoben, 1983). Under this view, advantages for concrete over abstract words come from differences in associations between words and previous knowledge (i.e., differences in the number of links, rather than the content of representation or organisational criteria), with abstract concepts being associated with a much more limited amount of context. Thus, the concreteness effect would result from the availability of sufficient context for processing concrete concepts in most language situations, but a deficient context for the processing of abstract words (Schwanenflugel & Shoben, 1983).

More recently, differences between concrete and abstract concepts and words have been discussed in terms of metaphorical extension (Boroditsky, 2000; Lakoff & Johnson, 1980, 1999) according to which abstract concepts would be learnt and understood in terms of the concrete domains to which they extend (e.g. the mind as a container). Such an account would assume different organisational principles for concrete and abstract knowledge. Kousta, Vigliocco, Vinson, Andrews and Del Campo (2011) have provided yet a different account for how abstract concepts and words are represented, based on the dual coding view proposed by Paivio but differing in how the content of abstract and concrete meaning is defined. In this view there are two classes of information that contribute to conceptual representation: experiential and linguistic information, and the differences between concrete and abstract word meanings arise due to different proportions and types of information for each: a preponderance of sensorimotor information underlying concrete word meanings and a preponderance of affective and linguistic information underlying abstract word meanings (Kousta, et al 2011).

Thus, to summarise, theories of meaning in language make assumptions concerning whether and how different domains of knowledge are represented within the semantic system. These assumptions can differ greatly varying from a single, unitary semantic system to a much more fractionated system, where different principles of organisation are specified for different word types. However, there exists no strong evidence for assuming different principles, and hence, following the argument of parsimony, I assume a unitary system based on the same principles across domains. Instead of different organisational principles, differences across domains come about due to differences in content, namely differences in the extent to which a given type of content is most important for a given domain (e.g. sensorimotor information for the concrete domain and emotion and linguistic information for the abstract domain (Vigliocco, Meteyard, Andrews & Kousta, 2009)).

1.3 The Theoretical Debate

Following from the description in section 1.1., I will now consider how the two broad approaches view semantic representation: symbolic/holistic approaches and embodied/featural approaches.

1.3.1 Symbolic/Holistic & distributional theories

1.3.1.1 Holistic theories

Holistic theories take a non-decompositional, relational view: the meaning of words can only be evaluated as a whole, in terms of relations between other words or entities, rather than being decomposed into smaller components. Words take their meaning from their relationships with other words, for example by associative links. In early versions of these theories, meaning was described in semantic networks (e.g. Quillian, 1968; Collins & Loftus, 1975) where a word was denoted by a single node in a network and its meaning by connections between other nodes. In Quillian's (1968) network model for example, a concept's properties are represented by labelled relational links with other concepts, and these links are described by 'criterialities' that determine how important each property is to that concept. The full meaning of a concept arises out of the whole network, beginning from the concept node, which has no content of its own.

Semantic similarity effects, such as semantic priming, are explained by holistic approaches (e.g. Quillian, 1967) in terms of spreading activation from an activated node (such as the prime or distractor word) to other concepts by connections existing between nodes. Response time in experimental tasks would be driven by the time it takes for a node to reach an activation threshold. Thus words that are semantically related will be closer together in the semantic space than semantically unrelated words and so activation spreads more quickly from the prime to the target word. One problem that exists for holistic explanations of semantic relatedness is that semantic effects can be graded. For example, in the neuropsychological literature, damage to semantic areas does not result in all or nothing deficits, but rather graded category-specific deficits, which can be more easily accounted for with featural theories (e.g. Vinson, Vigliocco, Cappa & Siri, 2003). Incorporating 'criterialities' in holistic models allows for effects of gradation, however a criticism remains that there are too many degrees of freedom given the different possible types of links and weightings (Johnson-Laird, Herrmann & Chaffin, 1984)

In some holistic models, differences between object-nouns and action-verbs have been modelled in terms of different relational links (e.g. Graesser, Hopkinson & Schmid, 1987; Huttenlocher & Lui, 1979). In Wordnet (Miller & Fellbaum, 1991) this is represented on a large scale with four distinct networks representing nouns, verbs, adjectives and adverbs. Nouns can be linked via relations such as hyponymy (i.e. belonging to a particular class: "*dog*" is a hyponym of "*animal*") and meronymy (i.e. being a part of a whole: "*mouth*" is a part of "*face*"). These relations are not as dominant for verbs, which instead tend to be linked by relations such as troponymy (i.e. being a particular manner of another verb: "*crawling*" to "*go/move*"), entailment (i.e. a necessary requirement of an action: "*snoring*" entails "*sleeping*") and antonymy (i.e. meaning the opposite: "*coming*" is the opposite of "*going*"). The representation of abstract words in Wordnet is no different to more concrete words of the same grammatical class, although abstract words tend to occur in shallower hierarchies (i.e. fewer superordinate terms; Changizi, 2008)

1.3.1.2 Distributional theories

Distributional theories are concerned with statistical patterns in language itself, for example in different types of texts or documents. The meaning of a word is described by its distribution across the language environment. Distributional approaches assign no role to sensory and motor information, using only information present in the linguistic data.

Dominant distributional approaches developed within cognitive science are latent semantic analysis (LSA, Landauer & Dumais, 1997), hyperspace analogue to language (HAL, Lund & Burgess, 1996) and more recently Griffiths et al's (Griffiths & Steyvers, 2002, 2003; Griffiths et al., 2007) topic model. All of these approaches use large samples of text, evaluating properties of the contexts in which a word appears in order to estimate its relationship to other words. For example, Landauer and Dumais (1997) took encyclopaedic text as the source corpus for analysis, and different articles in that encyclopaedia as separate contexts, under the assumption that related words will tend to co-occur in the same contexts. For each word occurring in the corpus they counted its occurrence in each of the contexts. LSA is the transformation of this sparse, high-dimensionality space of word occurrences into lower dimensionality. In contrast, HAL (Lund & Burgess, 1996) considers a word's context not in terms of separate documents but by local lexical context, characterising a word in terms of neighbouring words. Topic model, like LSA, considers words in terms of the contexts from which they are sampled, but differs in assumptions: contexts themselves have been sampled from a distribution of latent topics, each of which is represented as a probability distribution over words (e.g. Griffiths et al., 2007).

These models have successfully simulated semantic effects such as semantic similarity in semantic priming tasks. LSA has been shown to successfully simulate a number of human cognitive behaviours. For example, simulated scores on a standard vocabulary test have been shown to overlap with human scores and simulations can mimic human word sorting behaviour (Landauer, Foltz & Laham 1998). Thus, there is a strong correspondence between model performance and human behaviour suggesting that this technique can capture aspects of the representation of meaning as demonstrated in behavioural language tasks. If symbolic theories can successfully approximate human language comprehension then they should be considered valid models of human language processing, reflecting processes analogous to human language processing, to some extent (Landauer & Dumais, 1997).

Despite the power of distributional models in simulating human behaviour, some have argued that the statistical patterns that exist in language co-occurrences are merely epiphenomenal and in fact have no role to play in semantic representation (Glenberg & Robertson, 2000). That language-based models do not take into account the wealth of information available from other sources of meaning, such as bodily sensations, perceptions and introspections, as embodied theories do, is a fundamental criticism. Additionally, other types of information present in the text such as syntactic and morphological relations are typically ignored. But, LSA has been described as a method for analyzing the "verbal outcomes of all these juicy processes" (Landauer et al., 1998, p. 261) and thus provides a close approximation to the important knowledge underlying lexical meaning. Glenberg & Robertson (2000) are not convinced and argue "the computational manipulation of abstract symbols merely produces more abstract symbols, not meaning" (p. 19). Further, these models cannot account for the wealth of behavioural and neuroscientific evidence for the embodied framework, which links language to the brain's sensory-motor systems (reviewed in Chapter 2). One can use the famous "Chinese room" example (Searle, 1980; section 1.1.1) to highlight the importance of this argument.

1.3.1.3 Holistic theories and the key issues

Regarding the relationship between words and concepts, a strict one-to-one mapping is proposed between conceptual representations and lexical representations. Each lexical concept is equal to a single, abstract representation in the conceptual system. This means that the conceptual system must contain representations of all concepts that are lexicalized in all languages. And so, any lexical differences that appear cross-linguistically must be due to conceptual differences. In order to defend the universality of conceptual structure, one must assume that not all concepts are lexicalized in each language (see Vigliocco & Filipovic, 2004).

Relations between different word types here are not pre-specified and instead the same principles are used for all word types (Landauer & Dumais, 1997; Burgess & Lund, 1997). Differences between word types such as noun-verb differences and concrete-abstract differences are captured in the relationships that result from these statistical models, patterns that exist in the text itself. Thus, distributional models have no problem defining all domains, as long as they are represented in the source texts.

1.3.2 Featural and embodied theories

Embodiment places emphasis on sensorimotor features as building blocks of meaning. This emphasis is shared with featural theories according to which a word's meaning is seen as decomposable into a set of defining features (e.g. Collins & Quillian, 1969; Rosch & Mervis, 1975). Sets of conceptual features are bound together to form a lexical representation of the word's meaning. For example, the meaning of *chair* could be defined by features including <has legs>, <made of wood> and <is sat on>.

Featural properties of different word categories have been modelled to explain category-specific deficits in different forms of brain damage and to shed light on the organisation of the semantic system (Farah & McClelland 1991; Gonnerman et al., 1997; Devlin, Gonnerman, Andersen & Seidenberg, 1998; McCrae & Cree, 2002). By looking at the proportion of perceptual (e.g. <has fur>) and functional (e.g. <cuts food>) features for the categories of artifacts and natural kinds, Farah and McClelland (1991) described the topographic organisation of semantic memory in terms of modality rather than category. In their connectionist model, damage to perceptual features only caused a selective deficit for processing of natural kinds, whereas conversely, damage to functional features only caused a selective deficit to the processing of artifacts. Thus, what was once seen as a category-specific deficit emerged as a result of damage to specific feature types, suggesting that the organisation of semantic memory is in terms of sensorimotor features and not categories (Warrington & Shallice, 1984; Plaut & Shallice, 1991).

Featural theories describe semantic similarity between words in terms of featural properties such as featural correlations and featural overlap (Smith, Shoben & Rips, 1974; McRae & Boisvert, 1998). The role of feature correlations and featural overlap in semantic similarity has been supported by a range of behavioural tasks (e.g. Rosch & Mervis, 1975; McCrae & Boisvert, 1998). In an attribute-listing study for example, Rosch and Mervis (1975) showed that members of a category are considered most prototypical of that category if they share more features with other members of the same category and fewer features in common with other categories.

Featural theories have been applied to explain differences between words referring to objects (nouns) and words referring to events (primarily verbs referring to actions). The difference in how concrete nouns and verbs are represented in the semantic system is defined in terms of types of features and associations between features. The meanings of nouns are more differentiated, with dense associations between features and properties (Tyler, Russell, Fadili & Moss, 2001) across many different sensory domains (Damasio & Tranel, 1993). Looking at speaker-generated feature norms, Vinson and Vigliocco (2002) reported that objects tend to have more specific features referring to narrow semantic fields whereas verbs typically consist of features that can apply to a wider set of semantic fields and that have less sensory associations. These differences have been invoked to account for patients who selectively suffered in their ability to retrieve and produce nouns and those, who instead, had more problems with verbs (see Vigliocco, Vinson, Druks, Barber & Cappa, 2011). However, these theories do not extend to account for differences between concrete and abstract words, limiting their focus on more concrete words.

Featural theories usually focus on concepts, not words (although concepts and words are then often implicitly or explicitly assumed as the same). There are theories, however, that assume a separate semantic level where features are bound into a lexico-semantic representation (Vigliocco, et al 2004), and other neurological theories that hypothesize "convergence zones" in the brain where information from multiple modalities is integrated (Damasio, 1989; Simmons & Barsalou, 2003). These convergence zones have been argued as necessary to explain why sometimes category-specific deficits are limited to words and appear to spare conceptual knowledge (e.g., Cappa, Frugoni, Pasquali, Perani & Zorat, 1998).

Embodied theories build upon these earlier accounts and research that provides support for featural representations is also necessarily compatible with embodied views. For example, semantic priming based on overlapping features (McRae & Boisvert, 1998) could be explained by overlap in activation of the same sensorimotor area (e.g. Pecher, Zeelenberg & Barsalou, 2003)

1.3.2.1 Embodiment

Embodied approaches posit that understanding the meaning of words involves engagement of the systems used in perception, action and introspection (e.g., Barsalou, 1999a; Stanfield & Zwaan, 2001; Glenberg & Kaschak, 2002; Kousta et al., 2011). This approach focuses on the content of semantic representations rather than organization. Embodied theorists argue against amodal models of semantics that are said to be missing the vital link between meaning in language and experience in the world. In others words, it is unclear how the meaning of a word is understood if language is simply made up of arbitrary symbols that have no link to referents or experiences in the world (Harnad, 1990). Under embodied views, to understand the meaning of a word one uses the brain's sensorimotor systems in a similar way to how one actually experiences that concept. Thus instead of transducing information from experience into abstract symbols, the experience itself is, in a way, recreated (Barsalou, 1999a). Hence sensory and motor information form the content of semantic representation (Meteyard et al., 2012). For example, to understand the word ‘cat’ one would simulate perceiving the shape and colour of a cat, how they move, what sounds they make and what types of actions we make towards them.

It is primarily the sixth version of embodiment proposed by Wilson (2002; Table 1-1), that 'offline cognition is body-based', that the present thesis adopts to address the topic of meaning in language. This view postulates that aspects of cognition involve priming the motor system, without any form of overt movement. That is, many cognitive activities including mental imagery, working memory, episodic memory, implicit memory, reasoning and problem solving, and here, language processing, make use of covert motor programs. Mental structures that evolved primarily to be used for perception and action are thought to be ‘co-opted’ and used offline in cognition, without the need for any physical input or output. The use of these sensorimotor systems in offline cognition is referred to as ‘simulation’. In order to represent information from the world, we run simulations using these sensorimotor resources.

Theories of embodiment vary in terms of how strongly they define the role of sensorimotor systems in meaning. In terms of the continuum (from disembodied to fully-embodied) developed for semantic theories by Meteyard and colleagues (Meteyard et al., 2012, see Figure 1-2) distributional approaches could be considered to be on the extreme ‘disembodied’ end of the continuum, assigning no role to sensory and motor information (e.g. Landauer & Dumais, 1997; Griffiths et al., 2007). Weak embodiment assumes that semantic representations are partly instantiated by sensory and motor information and this information does have a representational role, but some degree of abstraction still takes place (e.g. Barsalou, 1999a; Farah & McClelland, 1991; Pulvermüller, 1999, Simmons & Barsalou, 2003; Tyler & Moss, 2001; Vigliocco et al., 2004). Areas adjacent to primary sensory and motor areas are involved in semantic representation and are reciprocally linked to primary areas, so that semantic processing can affect activation in these areas and vice versa. Finally, from a strong embodiment perspective, semantic processing necessarily activates sensory and motor information and is completely dependent upon it (e.g. Gallese & Lakoff, 2005; Glenberg & Kaschak, 2003; Zwaan, 2003).

Here, semantic processing takes place within primary sensorimotor areas and precisely the same systems are used for semantic processing and sensorimotor processing. Views at the extreme end of the continuum are unlikely explanations: semantic representation is neither fully symbolic nor fully simulated.

Label	**Unembodied**	**Secondary embodiment**	**Weak embodiment**	**Strong embodiment**
Semantic Content	Symbolic/Amodal	Amodal	Cross-modal integration/ Supramodal	Analogue/Multimodal
Neural Architecture	Semantic region(s) have no temporal or spatial overlap with sensory and motor areas	Region for amodal semantic content plus modality specific regions which code experiential attributes	Distributed network of areas which code integrated modal information, proximal to primary sensory and motor regions	Distributed network of areas within primary sensory and motor systems
Relationship to sensory-motor systems	Complete independence	Independent but associated	Partial dependence	Complete dependence
Explanation of interactions	Indirect activation	Secondary activation	Mediation	Modulation
Theories	Collins & Loftus (1975) Landauer & Dumais (1997) Lund, Burgess &Atchley (1995) Griffiths et sl. (2007)	Mahon & Caramazza (2008) Patterson et al (2007) Quillian (1968)	Barsalou (1999) Farah & McClelland (1991) Pulvermuller (1999) Simmons & Barsalou (2003) Vigliocco et al (2004) Louwerse (2007) Vigliocco et al. (2009)	Glenberg & Gallese (2012) Pecher, Zeelenberg & Barsalou (2003)

Figure 1-2. A continuum of embodiment. Adapted from Meteyard, Cuadrado, Bahrami and Vigliocco (2012).

A fully symbolic theory is problematic because there is no link between language and information in the world, which raises the grounding problem (Harnard, 1990). Based on the number of behavioural experiments looking at the interaction between language and sensorimotor processes, as well as the neuroscientific evidence for sensory and motor activations during semantic processing (as covered in Chapter 2), it is clear that sensorimotor systems do play a role in semantic processing. Strong embodiment is also seen as an unsatisfactory account: some degree of abstraction must take place in order to extract and combine features into the correct conceptual conjunctions. An account in line with weak embodiment seems most appropriate, where sensorimotor information plays an integral, representational role in semantic representation but there is some level of abstraction, that could be a convergence zone or collection of convergence zones (e.g. Damasio & Damasio, 1994), where relevant information is linked and combined into a lexico-semantic representation.

Version	Description	Criticism
Cognition is situated	Cognitive processes take place within the context of on going tasks, with continual perceptual inputs and motor outputs affecting performance.	Offline cognition, such as remembering, is ignored. Development of offline abilities is fundamental to human cognition.
Cognition is time pressured	Cognition operates under real-time constraints. Time pressure shapes cognition.	Most of cognition takes places offline: thinking, assessing planning.
We offload cognitive work onto the environment	Offloading onto the environment reduces cognitive demands. Example: counting on one's fingers	Having a causal role in cognition is not sufficient to be included in the system
The environment is part of the cognitive system	The mind, the body and the environment should be studied as a unified system.	
Cognition is for action	The function of cognition is to serve adaptive activity	There are many exceptions e.g. watching a sunset, reading. A weaker version is more appropriate: cognition is often *for* action, but in a more indirect, flexible and sophisticated manner.
Cognition is body-based	Mental structures that evolved for perception and action is 'co-opted' and used in offline cognition, without need for physical input or output	

Table 1-1. Six views of Embodied Cognition (Wilson, 2012).

1.3.2.2 Embodied theories and the key issues

Do embodied theories make a distinction between word meaning and conceptual knowledge? In terms of the continuum of embodied theories described above, as one moves further from abstract/symbolic theories to strong versions of embodiment, the content of semantic representation includes gradually more sensorimotor information (Meteyard et al., 2012), blurring the distinction between semantics and conceptual information. For example, those theories defined as 'weak embodiment' still posit some degree of abstraction from sensorimotor information, such as convergence zones (Damasio, 1989; Simmons & Barsalou, 2003), as described above. Strong embodiment on the other hand sees semantics as directly dependent on sensory and motor systems, thus does not make a distinction between word meaning and conceptual knowledge.

With regards to the representation of different semantic classes, since word meanings are thought to produce similar activation patterns to the representation of the real-world objects or actions described in the language, different types of words will necessarily have different patterns of activation. Differences in the semantic representation of objects and actions have clearly been demonstrated (see Chapter 2 for a full review of embodied findings). Neural differences in the processing of object-nouns and action-verbs have been shown both with neuropsychology (Damasio & Tranel, 1993; Warrington & McCarthy, 1987), and imaging data (Martin, Haxby, Lalonde, Wiggs & Ungerlieder, 1995; Pulvermüller, Lutzenberger & Preissl, 1999; Kable et al., 2002; Vigliocco, Warren, Siri, Arciuli, Scott & Wise, 2006). Here, it has generally been found that processing object-nouns involves activation of posterior sensory cortices while processing of action-verbs involves activation of fronto-parietal motor areas.

Traditionally, it has been argued that embodied theories have problems explaining how abstract concepts are represented. Abstract words pose a special problem because their content is not strongly perceptual or motoric, and as such, it is often argued that their meaning can only be represented in an abstract propositional form (e.g. Noppeney & Price, 2004). There are now, however, a number of hypotheses on how abstract concepts can be embodied. One hypothesis is that the meaning of abstract words is understood through metaphorical mappings. For example, comprehending a word like ‘argue’ could involve the activation of a vertical spatial metaphor (Richardson, Spivey, McRae & Barsalou, 2003), or one could conceptualize the mind as a container (Dove, 2009) because it holds information. Metaphor allows an abstract representation to be based on an extension of a more concrete experience-based concept that is grounded in perception and action. However, one can still think of many aspects of abstract knowledge that could not be accounted for by metaphor (Meteyard, et al 2012), such as scientific technical jargon (but see Glenberg (2011, p. 15) for a description of how even this can be embodied via metaphor). It is questionable whether metaphorical mappings really could be the foundation of learning and representation of abstract concepts or rather just provide a structure for concepts already in existence (Barsalou, 1999a).

Alternatively, it has been suggested that the difference between concrete and abstract words arises because of the number and type of simulations for each word type, in a similar vein to looking at differences in context (c.f. the context availability theory, Schwananflugel & Shoben 1983). The meaning of abstract words would be based on a wider range of simulations than concrete words, and tend to focus more on social, introspective and affective information than perceptual and motor (Barsalou & Wiemer-Hasting, 2005; Connell & Lynott, 2012a). Differences arise between the two word types because the type of information and situations relevant for abstract meaning is more difficult to access. Kousta et al. (2011) and Vigliocco et al. (2009) have described the difference between abstract and concrete concepts as arising out of the ecological statistical preponderance of sensorimotor features in concrete concepts compared to the statistical preponderance of linguistic and especially affective associations for abstract concepts. Despite these attempts, there remain abstract aspects of language that are still difficult to explain. For example, there are many more abstract and schematic elements of language, such as morpho-syntactic markers (Meteyard et al., 2012), which are not easily accounted for.

1.3.3 Integrated models

Despite the apparent divide between embodied and distributional theories, these two types of information can be integrated to form a more general model of semantic representation. The symbol interdependency theory (Louwerse, 2007) describes meaning as composed of symbols that are dependent on other symbols and symbols that are dependent on embodied experiences. Here symbols are built upon embodied representations, but although they are grounded, language comprehension can proceed simply via interrelations amongst other symbols in some situations. That is, not every single word encountered is grounded, but their meaning can be inferred from relations to other symbols that have been.

Vigliocco et al. (2009) describe language as another vital source of information, along with experiential information, from which semantic representations can be learnt. Statistical distributions of words within texts provide important information about meaning that can be integrated with sensorimotor experience. For example, a child could learn the meaning of the word *dog* via experience with dogs' perceptual features: having four legs, barking etc., as well as language experience of hearing "dog": it tends to occur with words such as *pet* and *animals*. Combining both distributions of information allows linguistic information to 'hook up' to the world, thus grounding it.

Modern computational work is also beginning to model semantic meaning by integrating experiential and linguistic information. It has been shown that models that combine both types of distributional data perform better in simulating semantic effects than either distributions alone (Andrews, Vigliocco & Vinson 2009). The underlying principles employed in distributional models can also be applied to other domains of experience, not simply linguistic data. John and Jones (2012) proposed a model integrating both perceptual information (in the form of feature norms) and statistical information from language. Here, a word's full meaning is denoted by the concatenation of perceptual and linguistic vectors.

There are some potential shortcomings to current integrated models. Since concrete feature norms are generated by speakers verbally and via introspection, using them as ‘embodied information’ means there are possible sensorimotor and affective aspects of experiential information that may not be included, suggesting that the findings cannot be generalized to all word types. However, other methods for appropriately modelling experiential information are being explored. Recent methods are beginning to combine information from computer vision with text in distributional models; models including visual information outperform distributional models based on text only, at least when vision is relevant to words' meanings (Bruni, Baroni, Uijlings & Sebe, 2012a; Bruni, Boleda, Baroni & Tran, 2012b). Future work will need to make use of more sophisticated types of perceptual information, as well as incorporating other aspects of bodily experience such as action and emotion.

1.4 Theories and hypotheses of embodied language processing

This section presents some of the most dominant theories and hypotheses of embodiment, summarizing the assumptions of each approach.

1.4.1 Perceptual Symbol Systems

Barsalou (1999a) proposes that meaning is constructed from ‘perceptual symbols’ (see Figure 1-1b). Unlike the symbols of traditional amodal theories, perceptual symbols are modal and analogical. Concepts are represented in similar systems to those of their real-world referents and in a multimodal manner: across sensory modalities, proprioception and introspection. A perceptual symbol is a record of a neural representation underlying a perceptual state in the sensorimotor areas of the brain. These representations were extracted from experience via selective attention and then stored in long-term memory to symbolically stand for referents. Perceptual symbols do not represent the entire brain state of a particular experience but rather schematic details: a componential rather than holistic representation (Pecher et al., 2003). They are also referred to as ‘partially-executed simulations’ (Glenberg & Gallese, 2011), partial because attention is selective (Wassenburgh & Zwaan, 2010). Perceptual symbols are dynamic: since they are based on associative patterns of neurons their reinstatement will not necessarily be the same each time. Thus perceptual symbols for concepts are not seen as strict, generic representations but rather vary as and when necessary in reference to a particular context.

Related perceptual symbols are organized into a simulator that allows the cognitive system to construct a simulation of an entity or event in its absence. Simulators are similar to mental models (Johnson-Laird, 1983): they are used for simulations of specific types of entities and events. A simulator contains two levels to its structure. The first is an underlying frame that integrates perceptual symbols across category instances. The second level contains an infinite set of simulations that can be constructed from the frame. Once a simulator is established in memory, it helps to identify category members on subsequent occasions.

1.4.2 The Immersed Experiencer Framework

Zwaan (2003) describes a framework for language comprehension where comprehension involves experiential mental simulation. Here mental simulation is described as the situating of "oneself in events outside of the here and now" (Zwaan & Kaschak, 2009) and in comprehension involves the "vicarious experiencing of the events being described" (Zwaan & Kaschak, 2009). Mental simulation involves very similar processes as those involved in actually carrying out an action. Simulations gradually evolve over time in the same way that events do. The comprehender is thus "immersed" in the described event and experiences objects and events as if really there. Using past experiences in the world, mental simulation allows one to understand how events unfold.

The Immersed Experiencer Framework (IEF) proposes three component processes of language comprehension: activation, construal and integration. Activation occurs at the word level where single words activate experiential information based of the word's referent via functional webs (Pulvermüller, 1999). Construal takes place at the level of clauses where functional webs are 'articulated' via constraint-satisfaction mechanisms and integrated into a mental simulation of an event. Finally experiential information is integrated to form a coherent meaning at the discourse level. Integration follows the constraints of human experience and is influenced by factors such as predictability and overlap with the existing mental simulation.

Construals contain components consistent with real world experience including time, perspective, orientation and distance and are dynamic. In line with Barsalou's

(1999a) perceptual symbol systems, construals exist in a schematic form. Aspects of the sentence or supporting context may highlight certain aspects of the situation, but features that are not necessary for comprehension are not activated. As in real-world perception, the amount of information attended to is constrained by attentional capacity.

The IEF allows for context sensitivity. Without context, single words activate overlapping functional webs, but the diffuseness of activation is decreased with increasing constraints from context, such as frequency or recency of experience with the referent or constraints from previous sentence context. The depth of a simulation in language comprehension depends on both the comprehender's own experience in the world and their language comprehension skill.

1.4.3 The Indexical Hypothesis

The Indexical Hypothesis (IH) proposes that meaning in language is grounded in bodily action (Glenberg & Robertson, 1999). Three steps are outlined to describe how language is understood in specific contexts. Firstly, language is mapped onto entities in the environment or onto perceptual symbols (Barsalou, 1999a) contained in memory. Affordances are then derived from activated representations, facilitating preparation for action. These affordances are then combined or meshed together to produce a simulation of the event, a coherent pattern of action (Kaschak & Glenberg, 2000) and thus successful comprehension of a sentence (if the affordances can be successfully meshed). Meshing is constrained both by the biological/physical properties of the objects involved and by the syntax of the sentence. For example, compare the three sentences below:

1. *The man hung his coat on the chair*

2. *The man hung his wardrobe on the chair*

3. *The man hung his coat on the vacuum*

All three sentences are grammatical, but the meaning of (2) is impossible because the affordances of the objects cannot be meshed. (3) may at first appear odd, but this is due to the novelty of the action that is described. It is only when simulating the affordances of the objects described that the action becomes perfectly sensible: the shape of the vacuum allows the coat to be hung upon it.

1.4.4 Language as Situated Simulation (LASS)

Barsalou, Santos, Simmons & Wilson (2008) propose the Language as Situated Simulation account (LASS) where language processing is described as requiring two processes; an early activation of linguistic representations, such as statistical associations, taking place in language areas of the brain and a later situated simulation involving sensorimotor systems. Linguistic representations are activated earlier due to their similarity with the incoming stimuli. Sometimes this activation is enough for tasks that require shallow and superficial processing. Linguistic representations are used as pointers to the associated semantic information in the form of simulations. Thus, the simulation process begins soon after the linguistic representations have peaked.

Evidence for the timing of linguistic activations and situated simulations can been found in property generation tasks (e.g. Santos, Chaigneau, Simmons, & Barsalou, 2011). These tasks involve participants naming as many properties of an object in a certain time. From the LASS framework, it would be expected that properties would initially be taken from the linguistic system (such as word associations) and later properties would reflect the simulation process (such as physical characteristics). This is exactly the pattern of results that has been found (Santos et al., 2011). Additional evidence was found using fMRI comparing brain activations between a property generation task, a word association task and a situation generation task (Simmons, Hamann, Harenski, Hu, & Barsalou, 2008). Activations in the first 7.5 seconds of the property generation task were found to most similar to activations in the word association task (a linguistic task) and activations in the later half were more similar to situation generation task (requiring simulation).

1.4.5 Body specificity hypothesis

To test the proposal that the meaning of words is grounded in one's perceptual and motor experiences, as predicted by all embodied theories, we can look at how people with different bodies think. Embodied theories predict that those with different bodies should develop different concepts. This prediction is clearly specified in the 'body specificity hypothesis' (Casasanto, 2009). Since the body is a constant presence in all experience it should strongly influence the nature of the representations formed. The body constrains the way people perceive and act in the environment (e.g. Linkenauger, Witt, Stefanucci & Proffitt, 2009), thus the type of experience the body leads one to have has strong implications for the nature of mental simulations during action language processing. This 'body relativity' is analogous to linguistic relativity effects described in section 2.1. That is, in a similar way to how people who speak different languages think differently about the world in predictable ways, so do people with different bodies think differently about the world in predictable ways.

There are now many studies providing support for the body-specificity hypothesis. For example, when told to imagine the hand or to read action words describing actions normally performed with the dominant hand differences in motor activity are observed between left and right-handers (Willems, Toni, Hagoort & Casasanto, 2009; Willems, Hagoort & Casasanto, 2010). This suggests that word meanings do not have a fixed representation across individuals but rather vary based on the type of real world experience that individual has. The body specificity hypothesis has also been offered to explain comprehension of more abstract language, such as emotional valence. In order to understand the abstract concept of valence people ground the meaning of valenced words in the more concrete domain of space (Casasanto, 2009). Typically people tend to assign "good things" to the "right" side of space and "bad things" to the "left" side of space. The body specificity hypothesis explains this effect in terms of handedness. Right-handers more easily interact with the right side of space than the left, which is instead clumsier. In fact, left-handers show the reverse valence mappings, with "left" more positive than "right" (Casasanto, 2009).

Body-specific findings suggest that people tend to understand action language in terms of their own actions, using their own bodies, rather than the bodies of others. The default perspective in action language comprehension therefore may be egocentric, based on one's own experience, not a generalization to action in others.

Simulation of others' action is likely to occur when the sentence context specifically focuses on a particular agent or context.

1.5 Assessing embodiment

1.5.1 How is language embodied?

An important question that is often raised in relation to embodied theories regards development. How is it that sensory and motor patterns come to stand for the meaning of words and sentences? Pulvermüller (1999) describes how a larger associative network of brain areas becomes implicated in language processing due to functional links created between cortical language areas and sensory and motor areas during language acquisition. Adopting a Hebbian perspective (Hebb, 1949), language has the possibility of recruiting neurons in different cortical areas as part of a larger, distributed functional unit via associative learning. Such functional units (or cell assemblies) form during word learning, when a word and its referent are experienced. For example, if a word frequently co-occurs with a particular visual stimulus, then strong connections will be made in the cortex between neurons in visual areas and neurons in language areas (Neininger & Pulvermüller, 2001). Subsequently, once a word is encountered, neurons associated with the word form activate at the same time as those from other modalities associated with the meaning of the word, for example, the perception of the object being referred to, information about how to use the object (affordances) or how one feels in the situation. Recurrent activation of the particular neurons result in a higher-order assembly to be utilized in future occurrences of the word in question. Once a higher-order assembly is established between the neurons related to the word form and those related to the perception of and actions towards the word's referent, a phonological signal will be sufficient to activate the whole assembly. The cortex has been described as "a storehouse of words and their meanings bound together by distributed neuronal systems with specific topographies" (Pulvermüller, Hauk, Nikulin & Ilmoniemi, 2005, p. 797).

Along similar lines Glenberg and Gallese's (2012) theory of action-based language adopts existing theories of action control (Wolpert, Doya & Kowato, 200; Haruno, Wolpert & Kowato, 2003) and describes language learning, comprehension and production as the link between speech controllers, action controllers and predictors. Here a controller (also referred to as a backward or inverse model) computes motor commands, and a predictor (also referred to as a simulator or forward model) predicts the sensory and motor effects of any actions. Word learning occurs when attention is drawn to a particular object and its action controllers are activated, and simultaneously the child's speech controllers are activated when the parent names the object. Meaning is learned by connecting the activated action controller with the activated speech controller. This theory predicts that children should learn the meaning of verbs more proficiently if they have first learned their corresponding actions. Support for this account of learning comes from the MacArthur Child Developmental Inventory data (Angrave & Glenberg, 2007), showing that children's development of speech occurs in lockstep with the development of actions, although speech is typically around a year delayed. When comprehending language, speech controllers are activated as a form of covert imitation, which in turn activates corresponding action controllers for the meaning of the words. Following this, forward models are generated via predictors and the perceptual or motor consequences of the action controllers are anticipated. This is simulation.

Why is language embodied? It is likely that mental simulation during language comprehension occurs to serve an important function. Barsalou (1999b) proposes that simulation likely developed to support situated action. Using language, one can control the simulations of others and induce intended action and perceptual states that can lead to social coordination. Furthermore, the purpose of language is to prepare oneself for future actions (Barsalou, 1999b), such as actions on objects or interactions with others. Therefore, mental simulation is well suited to prepare one for action because simulations occur in the same format as real-world perception and action. This is also in line with Glenberg and Gallese's theory of action based language (2011).

1.5.2 Criticisms of embodiment and further questions

Critics have argued that perceptual and motor simulation may simply be an epiphenomenal effect and may be the result of spreading activation from amodal representations to perceptual areas via indirect, associative routes due to the correlation between the two (Dove, 2009; Mahon & Caramazza, 2008). Mahon and Caramazza (2008), for example, argue that the existing behavioural and neuroscientific evidence (presented in Chapter 2) can be explained by unembodied theories: theories that describe semantic information as independent to sensory and motor information. The observed interactions could come about via an indirect route, for example, semantic information may engage working memory systems which in turn recruit sensory motor systems (Meteyard et al., 2012, p.3) Or motor cortex activations may be the result of motor imagery instead of simulations. In terms of this hypothesis, one might expect to observe bilateral effects for brain activations opposed to the typically observed left-lateralized activations (Oliveri, Finocchiaro, Shapiro, Ganitano, Caramazza & Pascual-Leone, 2004). On the other hand, motor imagery might show a bias towards the left motor cortex since most subjects are likely to use their right hand to perform the type of actions described by the experimental stimuli

A commonly raised question about embodied simulation is its necessity. Do we need simulation in order to understand language or is it an epiphenomenal effect (Mahon & Caramazza, 2008), with activation in sensorimotor areas simply being the result of spreading activation between dissociable systems? Looking carefully at the temporal dynamics of the interaction between language and the sensorimotor systems could address questions of epiphenomenalism. If language comprehension necessarily recruits sensorimotor systems, then such effects should be observed very early on in processing (Pavan & Baggio, 2012).

Related to this is the issue of depth of processing. It is unclear whether simulation occurs under all circumstances in all language tasks. Simulation may not be necessary for shallow language tasks, where a good-enough representation could be inferred simply from the linguistic data alone, using statistical relations existent between words (Barsalou et al, 2008; Louwerse, 2011). Embodied simulations could instead be reserved for deeper levels of processing.

It is clear that to move forward, embodied theories now need to further investigate the different mechanisms that underlie the wealth of empirical data and formulate a clear and precise description of the specific nature of these processes and their temporal properties. In the next chapter I thoroughly discuss research evidence for embodied theories and attempt to address some of the issues raised in this final section.

1.6 Chapter Summary

The fundamental goal of communication is to understand meaning. This chapter discusses how meaning in language is represented. There are two dominant approaches in cognitive science to how meaning is represented in the mind: symbolic theories that posit meaning is composed of abstract, arbitrary and amodal symbols, and embodied theories that posit meaning is composed of sensorimotor information. Recently, cognitive science has begun to reject symbolic theories because they face the grounding problem: meaning retrieval is impossible if symbols are not linked to the world. By assigning a role to sensorimotor processing, embodied cognition solves this problem.

Taking a symbolic perspective, distributional theories of semantics (evolved from holistic models (e.g. Quillian, 1968; Collins & Loftus, 1975)) describe meaning in terms of statistical relations between words and assign no role for sensory and motor information (e.g. Landauer & Dumais, 1997; Lund & Burgess, 1996; Griffiths & Steyvers, 2002, 2003; Griffiths et al., 2007). These models face the grounding problem; however recent models combining distributional and experiential information perform better in modelling semantic behaviour than either distributional or experiential information alone (Andrews et al., 2009).

Embodied approaches to semantics (evolving from featural models) describe language processing as involving simulation in the brain’s perception and action systems (e.g. Barsalou, 1999a; Glenberg & Robertson, 1999; Zwaan, 2003). The link between words and sensorimotor information develops throughout the lifespan via Hebbian learning mechanisms (Pulvermüller, 1999) and is thought to be in service of situated action (Barsalou, 1999b). Embodied theories of language processing have been well supported, with many experiments showing recruitment of sensorimotor systems during language comprehension (as summarized in the next chapter). However, critics argue that embodied activations can be explained by non-embodied processes, such as spreading activation or mental imagery (e.g. Mahon & Caramazza, 2008). Within Chapter 2, I describe evidence for embodiment while addressing these issues.

Chapter 2 Literature Review

2.1 Aims

This chapter presents a detailed literature review of experimental findings within the embodied literature across several different experimental methods: behavioural, functional magnetic resonance imaging (fMRI), electroencephalography (EEG), transcranial magnetic stimulation (TMS) and patient data, with each serving a particular methodological advantage in terms of testing embodied theories. Each section in this chapter describes a particular research methodology and attempts to address some fundamental issues existent in embodied theories. Behavioural and fMRI are the most dominant methods applied in this field and will be covered in greater depth. Although EEG, TMS and patient data receive less attention here, the evidence they provide is critical to embodied theories. There has been a wealth of studies providing evidence for mental simulation but now research needs to go beyond simply demonstrating interactions between language and sensorimotor processes to further describe the nature and the details of the mechanisms involved. Based on this, within this chapter I outline four issues that I view as fundamental in embodied research and present a literature review of studies in embodiment with reference to them. Below I briefly describe each issue.

2.1.1 Features

What aspects of our experience in the world do we simulate when we understand language? I will give an overview of different semantic domains that have been investigated in embodiment and provide evidence for simulation of different features of objects or events. Most existing research focuses on concrete objects and their features (for example, object shape (Zwaan, Stanfield & Yaxley, 2002)), but there is growing evidence for the embodiment of abstract concepts (e.g. Kousta et al 2011). Abstract language poses a special problem for embodied theories because their content is not strongly perceptual or motoric, and as such, it is often argued that their meaning can only be represented in abstract propositional form. It is thus unclear whether simulations in the service of language reflect the full range of experience that people have in the world, or instead if they focus on only salient aspects or schematized versions of the world.

2.1.2 Specificity

Related to features that are included in a simulation is the nature and detail of simulations. It is unclear how specific mental simulations are. Simulations may be broad, general representations with experiential information schematic and abstracted (Barsalou, 1999a; Zwaan 2003). However experiments have shown that simulations can be specific in terms of the features that are included, for example, information about the specific effector used in action simulations (Hauk et al., 2004). As with defining the types of features represented in simulations, this evidence helps to understand how closely simulations mirror our real-world experience and at what grain information is represented.

2.1.3 Mental simulations are post-comprehension mental images, and other criticisms

Critics of embodiment often propose that the simulations observed across experiments are not evidence for the involvement of sensorimotor systems in comprehension but instead reflect mental imagery processes or post-comprehension process that are not critical to understanding (Mahon & Caramazza, 2008). I will discuss evidence in support of a simulation account and not a mental imagery account. This evidence includes information about the time course of simulations: if simulations are automatically recruited during comprehension then effects should be seen early (e.g. Kiefer, Sim, Herrnberger, Grother & Hoenig, 2008).

2.1.4 Context

There is growing discussion about how the involvement of simulation in language comprehension is dependent on contextual factors and may not be necessary in all language contexts (Zwaan, 2014). Investigating the role of context in simulation can help reconcile conflicting results in the literature. Simulations have been shown to be flexible and hence more- or less-recruited dependent on environmental factors, linguistic factors or cognitive factors (Lebois, Wilson-Mendenhall & Barsalou, 2014).

In sum, there are four main issues in embodied research that need to be addressed in order to provide an accurate description of the simulation process and how it is recruited in different contexts. Below I present a review of current findings within the embodied literature and how these findings related to these four fundamental issues.

2.2 Behavioural evidence

Behavioural evidence demonstrates sensorimotor involvement in language processing typically through interactions between semantic content of words and real sensory stimuli. By combining language that describes actions or perceptual features with real action or perceptual tasks, one can assess whether language processing shares resources with perception and actions systems. If both tasks recruit similar processing systems, then their combination should affect processing in some way. Interference between language and action may occur due to competition for common resources (Boulenger, Silber, Roy, Paulignan, Jeannerod & Nazir, 2008) or facilitation could occur due to preactivation of critical regions (Connell & Lynott, 2014). This basic idea has been adopted across many experiments investigating mental simulation for different types of language.

2.2.1 Action language

Action language has been the most thoroughly investigated language type with experiments looking at the effect that actions have on the processing of action language and conversely, how action language can affect action production.

Glenberg & Kaschak (2002) describe a phenomenon known as the action-sentence compatibility effect (ACE). In the ACE paradigm, participants read sentences that describe actions towards or away from the body (e.g. "*Open/Close the drawer*) and have to decide whether the sentence makes sense by responding with a specially constructed button box that requires action either towards or away from the body. For some subjects, the "yes" button is close to the body, for others it is away from the body. The typical "ACE" effect is that participants are faster to decide that sentences make sense when the direction of their own response is compatible with the direction of movement described in the sentence. For example, faster responses are found in judging the sentence "*Close the drawer*" when responses were made with movement away from the body compared to towards the body. Thus, understanding the sentence involves, at least to some extent, the same processes as those used in making the physical action of closing the drawer.

Action effects have also been found for object nouns whose referent requires particular actions towards them. Processing words that denote manipulable objects that typically evoke actions towards or away from the body (e.g. a *key* requires movement away from the body, towards a door, and a *cup* requires movement towards the body, towards the mouth) was facilitated when an action was planned in the same direction as the object's typical movement (Rueschemeyer, Pfeiffer & Bekkering, 2010).

Reading adjectives has been shown to affect online movement kinematics (Gentilucci & Gangitano, 1998; Glover & Dixon, 2002). Glover & Dixon (2002) had participants reach and grasp objects of three different sizes that were labelled "LARGE" and "SMALL" (regardless of the true object size) whilst their movements were tracked with an overhead infrared video camera. Participants were told to ignore the word labels. Semantic effects of the words were found early on during the movement, with larger grip apertures to objects labelled with the word "LARGE" than objects labelled with the word "SMALL", with the difference decreasing over the course of the movement. The same effect on grip aperture has been found using word labels for large ("APPLE") and small ("GRAPE") objects (Glover, Rosenbaum, Graham & Dixon, 2008). The words automatically activate the affordances of the meaning of the words even though they were not helpful to the task (in a similar way to the automatic colour activation of colour words in the Stroop task (Stroop, 1935)).

Action simulations include information about the specific body parts used in an action. By manipulating how responses were made in a go/no-go experiment with action-related sentences, Buccino, Riggio, Melli, Binkofski, Gallese & Rizzolatti (2005) revealed the effector-specificity of motor involvement in sentence comprehension. Participants listened to sentences describing abstract actions, actions performed with the feet or actions performed with the hands and had to make a response when the sentence described a concrete action. Participants were instructed to respond either with their hand or with their foot. Response times in the task were found to increase when the motor response (hand or foot) matched the effector involved in the action described in the sentence. When listening to the sentences participants recruited the motor cortex in an effector-specific manner which subsequently interfered with the their motor response.

2.2.2 Perceptual language

Research conducted by Zwaan et al (e.g. Stanfield & Zwaan, 2001, Zwaan et al, 2002, Zwaan, Madden, Yaxley & Aveyard, 2004) has shown that during language comprehension, one creates a simulation of an event or entity that includes specific information about its visual features. For example, readers represent the fact that a nail has a different orientation if it is being hammered into the ground rather than into the wall (Stanfield & Zwaan, 2001) and that an eagle would be viewed with its wings outstretched if it was flying in the sky compared to sitting in its nest (Zwaan et al., 2002). In both experiments, readers read sentences that described objects in a particular location, with the location implicitly modifying either the shape or the orientation of the described object. After reading each sentence participants saw a picture and had to respond as to whether or not the picture was mentioned in the sentence. Results showed that responses to the picture were faster when the shape or orientation of the object in the picture matched that of the object described in the sentence, compared to when they did not, even though these features were never explicitly mentioned in the sentence. The readers had built a mental representation of the situation described by incorporating experiential information about the objects' visual features from their existing knowledge and experience with real-life entities with the current linguistic information.

Similar evidence has shown that spatial features are activated during mental simulation. Zwaan & Yaxley (2003) found that single words, without any sentence context, could activate spatial information related to their referent object. Participants were presented with words displayed in a spatially iconic configuration (for example '*attic*' above '*basement*') or a spatially non-iconic configuration ('*basement*' above '*attic*') and were asked to make semantic-relatedness judgements (i.e. "are these words semantically related?"). Participants were faster to make a semantic judgment about the word pairs when they were in an iconic (spatially congruent) configuration than a non-iconic (spatially incongruent) configuration. That is, they were faster to make judgments when the words were in the same spatial configuration as they are in the world. This suggests that reading the words activated the spatial features of the objects and hence facilitated responses when the spatial location of the words on the screen matched them. When the word pairs were presented horizontally, no differences were found, ruling out any explanation of the results based on word order (but see Louwerse & Jeuniaux, 2008, described in Section 2.5).

During comprehension of motion sentences, dynamic simulations are generated. Comprehenders simulate motion during language comprehension via some of the same mechanisms involved in visual perception of motion. Not only is motion in general simulated, but also more specifically, comprehension is sensitive to *direction* of motion. Kaschak, Zwaan, Averyard and Yaxley (2006) found that participants were slower to respond to a sentence describing motion in a certain direction when a concurrent visual stimulus displayed motion in the *same* direction as that described in the sentence. The direction of motion was not explicitly stated but was apparent upon simulating the meaning of the described action, for example "*The car approached you*" and "*The car left you in the dust*". This effect was present during a sentence sensibility task and a more shallow grammaticality judgment task. Thus, the sentence produced visual simulations of motion even when the task did not require deep levels of comprehension. Similarly, Zwaan et al. (2004) presented participants with sentences describing objects moving towards or away from the body (e.g. "*Tom threw the ball to you*" vs. "*You threw the ball to Tom*") and then asked them to respond to an image onscreen. Responses were much faster when the size of the object on screen matched the relative size it would be if the object was moving in the same direction as that implied in the sentence (e.g. a ball coming towards you would appear larger than one which had been thrown away from you). Both studies suggest that perceptual motion is simulated during language comprehension.

Studies have show that comprehending language describing upward or downward motion affects visual perception processes (Meteyard, Bahrami & Vigliocco, 2007; Pavan, Skujevskis & Baggio, 2013; Francken, Kok, Hagoort & de Lange, 2014). For example, Meteyard et al. (2007) looked closely at the relationship between language processing and visual perception using psychophysics (see Chapter 6 for further discussion). Whilst listening to motion verbs, participants performed a motion-judgment task in which they had to indicate whether they saw motion or not in a visual stimulus containing random dot kinematograms. At threshold levels of visible motion it was found that motion detection improved when heard motion verbs described motion in the same direction as that of the visual motion. For example, visual discrimination of upwards-moving dots was hindered when processing downward direction verbs (e.g. "dive") compared to verbs with the same direction (e.g. "rise"). Conversely, it has been shown that lexical decision to direction verbs is hindered when participants concurrently perceive motion of a matching direction at near threshold levels (Meteyard, Zokaei, Bahrami and Vigliocco, 2008). The relationship between language processing and visual perception is therefore bidirectional.

2.2.3 Simulation over imagery

To determine whether interactions between action language and actions is due to mental simulation or due to more explicit mental imagery, Boulenger et al (2008) presented participants with action words that were displayed too quickly to be consciously perceived (i.e. they were presented subliminally) during movement preparation. Because the words were not consciously perceived they could not have led to mental motor imagery. Visual cues were presented to indicate when a participant should prepare a motor act and when they should perform the motor act (reaching and grasping an object). Action words and concrete words were subliminally presented between these two visual cues and movement kinematics were recorded. Wrist acceleration peaks were reduced in the action verb condition compared to the concrete noun condition. Thus action words interfere with movement preparation compared to concrete words even when they are not consciously perceived, supporting a simulation and not mental imagery view.

2.2.4 Direction of effects

Within the behavioural findings, some studies have found facilitation of responses when features of a perceptual or action stimulus match that of the linguistic stimuli, but other studies find interference. Both results are seen as support for embodied theories: the two types of stimuli are interacting, suggesting that they share processes at some level, but defining the factors that lead to these differences will provide further understanding of the simulation process. For example, Glenberg and Kaschak (2002) found that semantic judgments were faster when direction of a physical response matched the direction described in the language (facilitation). However, Kaschak et al. (2006) found responses were slower when the direction of motion of an auditory stimulus matched the direction described in language (interference). Certain properties of the stimuli and details of their presentation could explain the opposing results. The dynamics of the interaction effects could be influenced by the match in modality of the presented linguistic and perceptual stimuli: Kaschak et al. (2006) presented linguistic stimuli visually and motion stimuli auditorily and found interference effects, however, the effect reversed when both stimuli were presented auditorily. Timing of stimulus presentation could also be a crucial factor in determining the direction of interaction effects: Boulenger, Roy, Paulignan, Deprez, Jeannerod and Nazir (2006) found interference effects when verb processing and a reaching movement were concurrent, but found facilitation effects when the same processes occurred consecutively. Interference is likely to occur when the two stimulus types are presented simultaneously because the necessary cognitive resources are not available to perform both tasks at the same time, but facilitation can occur when there is a delay in presentation because priming is more likely to occur (Bergen, Lindsay, Matlock & Narayanan, 2007). Another account of the differences in the direction of effects when a perceptual stimulus is combined with linguistic stimuli is in terms of perceptual attention (Connell & Lynott, 2012b): when the perceptual stimulus occupies attention it can lead to interference when there are few attentional resources available to aid in simulation, alternatively if the perceptual stimulus merely directs attention, but leaves resources available for simulation, it can lead to facilitation. Further tests of the mechanisms underlying these effects need to be further explored. In their current form, embodied theories are unable to make clear predictions, in terms of both simulation of perception and action, as to whether an experiment will lead to facilitation or interference and there are likely to be many factors at play.

2.2.5 Contextual factors

Research has revealed many factors that may affect the occurrence and nature of simulations during comprehension. One factor that may modulate sensory and motor activation is the depth of processing in comprehension. Shallow and deep processing differ in terms of how much semantic information is recruited. Shallow processing has been described as underspecified and incomplete and deep processing as specified and complete (Louwerse & Jeuniaux, 2008). Following the method of Zwaan & Yaxley (2003), as described in Section 2.2, Louwerse & Jeuniaux (2008) manipulated both iconicity (whether they presented in a spatially congruent or incongruent configuration) and semanticity (word associations) of word pairs. Word association measures were taken from LSA (Landauer & Dumais, 1997; described in Chapter 1, Section 3.1.1) and items were divided into high and low association groups (i.e. word pairs that are highly associated with each other and word pairs that are not). These measures reflect statistical patterns existent in text and no information about semantic content of words (see Chapter 1 Section 3.1.1). They found that in a 'deep' semantic task (semantic judgment) both iconicity and semanticity predicted response times, but for a more shallow task (lexical decision) only semanticity predicted differences. The authors argue that there is no doubt that language is embodied, but that embodiment is not "always *necessary* to language comprehension" (p. 1317). Instead, language processing can proceed via mechanisms that are simply "good enough" (Ferreira, Ferraro & Bailey, 2002). Strong versions of embodiment advocate that simulation is fundamental to comprehension, meaning that simulation a *necessary* part of the comprehension process, but Louwerse & Jeuniaux (2008) define fundamental as "synonymous with deep-rooted" (p.1).

Bergen et al. (2007) argue that mental simulations develop when the meanings of single words are integrated into a larger sentence structure and not for lexical associations of words alone. Using an object categorization task they found that sentences describing events that were up- or down- related interfered with object categorization when the object occurred in the same part of the visual field as that in the sentence. Importantly this interference was only observed when up or down-related nouns (e.g. *The* cellar *flooded* and *The* ceiling *cracked*) and upward or downward motion (e.g. *The cork* rocketed and *The glass* fell) were described in the sentence, but not for metaphorical motion (e.g. *The market* sank and *The amount* rose) or abstract verbs (e.g. *The ratio* lessened and *The fees* expanded). The authors concluded that spatial simulations of motion are used for sentences about literal upward or downward motion but not for non-literal sentences that include words with upward and downward associations. That is, simply presented a word with upward or downward associations is not enough for a simulation of upward or downward motion to develop. Other studies however suggest that motor simulation does occur even in sentences where an action verb has a non-literal meaning (Boulenger, Hauk & Pulvermüller, 2009)

Grammar has also been shown to have a modulatory effect on mental simulations. Bergen and Wheeler (2010) adopted the ACE paradigm (Glenberg & Kaschak, 2002; described in Section 2.1) using sentences describing hand motions and manipulated meaning by modifying grammatical aspect so that the sentence described either an on-going action or a completed action (e.g. *Chris is patting the cat* versus *Chris patted the cat*). The typical ACE effect (facilitation of responses for conditions where the direction of response matched direction described in the sentence) was observed for progressive sentences but not for perfect sentences. In line with the sentence meaning, motor simulations occurred for continuing action but not for actions described as completed. Thus, grammatical aspect serves to modulate how the mental simulations elicited by the content words in a sentence are enacted.

Similarly Anderson, Matlock, Fausey & Spivey (2008) found that manipulating simple morphological information could change the duration and pattern of a simulated event. Participants' task was to place a character in the appropriate place in a scene according to the sentence. It was found that the character was placed closer to the beginning of a to-be-used path and had longer mouse movement durations in completing the task when they heard a sentence with a past progressive (e.g. "Tom *was jogging* to the woods and then stretched when he got there") than a simple past tense (e.g. "Tom *jogged* to the woods and then stretched when he got there"). Thus, grammatical aspect influenced how the event was simulated; with a past progressive the event was seen as on going in comparison to a simple past tense where the event was seen as completed.

Thus, there are several factors that affect whether or not evidence of simulation is observed in behavioural measures. These include cognitive factors, such as depth of processing as well as linguistic factors such as grammatical and morphological information. Researchers are beginning to see the necessity of explicating the factors involved and ascertaining their significance (e.g. Zwaan, 2014; Lebois et al., 2014).

2.3 Functional magnetic resonance imaging (fMRI)

If modality-specific areas of the brain are recruited during mental simulation then they should be activated during language processing. One of the best methodologies for testing these claims is functional magnetic resonance imaging (fMRI). fMRI allows one to look at the change in blood oxygen levels (BOLD) in the brain whilst completing cognitive tasks within a scanner. By carefully designing experimental conditions (such as listening to words from a particular semantic category) and appropriate control conditions (such as listening to words from a different semantic category), areas of the brain involved in the task of interest can be localized via a process of subtraction. There are now numerous studies showing modality-specific activations during language comprehension, as summarized below (see Figure 1, taken from Binder & Desai (2011) for visual depiction of modality-specific activations during comprehension). However, it should be noted that using fMRI only provides a correlational measure and thus one cannot establish whether simulations are necessary using this method.

2.3.1 Action language

As with behavioural work, the majority of fMRI studies focuses on action words. There are now many fMRI studies showing activation of the motor and premotor cortex for single action words, such as *kick* and *pick* (Hauk et al 2004, Kemmerer, Castillo, Talavage, Patterson & Wiley, 2008), action phrases like *grasping the pen* (Aziz-Zadeh, Wilson, Rizzolatti & Iacoboni, 2006), action sentences like *I bite an apple* (Tettamanti et al 2005, Boulenger et al., 2009) and longer discourse (Kurby & Zacks, 2013). Motor activation has also been observed for non-literal meanings of sentences. Boulenger et al.(2009) found somatotopic motor activation for idiomatic sentences such as *Pablo kicked the habit*, suggesting that even when the true meaning of the sentence does not involve action, the action related to the meaning of the words is still activated. This however is in opposition to the study discussed earlier (Bergen et al., 2002) where spatial simulations were observed for the literal meaning of words but not for non-literal meanings, as well as evidence described below (Section 3.5) that did not find motor activation for motor verbs used in idiomatic sentences (Raposo, Moss, Stamatakis, Pulvermüller & Tyler, 2006).

Action simulations have also been observed for words that do not describe actions themselves but objects that typically require particular actions (Chao and Martin, 2000; Saccuman, Cappa, Bates, Arevalo, Della Rosa, Danna & Perani, 2006; Rueschemeyer, van Rooij, Lindermann, Willems & Bekkering, 2010b). For example, Chao and Martin (2000) observed left ventral premotor and left posterior parietal activations, areas that store information about motor-based properties, when participants named tools, suggesting that part of the meaning of those tools includes the associated actions that one would perform with them.

2.3.2 Perceptual language

Studies have described activations for perceptual features of objects including visual (Pulvermüller & Hauk 2006, Simmons, Ramjee, Beauchamp, McRae, Martin & Barsalou, 2007; van Dam, Rueschemeyer & Bekkering, 2010), auditory (Kiefer et al., 2008) and olfactory-gustatory features (Gonzalez, Barros-Loscertales, Pulvermüller, Meseguer, Belloch & Avilia, 2006). Pulvermüller and Hauk (2006) found colour-related words (e.g. *brown*, *blonde*) preferentially activated anterior parahippocampal gyrus, an area typically involved in colour categorization of objects. Kiefer et al. (2008) found that words with auditory associations activated regions within the auditory association cortex (left posterior superior temporal gyrus and middle temporal gyrus), areas that were active when listening to real world sounds in a second task. Moreover, activation to the words was linearly modulated by the relevance of their acoustic factors as rated by a separate set of participants. Words have also been shown to activate smell and taste regions, perceptual features that are perhaps less salient or less dominant in our everyday experiences: during a single day we notice and orientate ourselves around more visual and auditory features, e.g. looking where something is, listening to somebody speak (see Chapter 5 which explores multimodality), rather than through one's sense of smell or taste.

Gonzalez et a.l (2006) found that silently reading words with strong ratings of associated odour (e.g. *cinnamon*, *garlic*) activated the primary olfactory cortex compared to neutral words. Similarly, Barros-Loscertales et al. (2012) found activations in primary and secondary gustatory regions for words with strong taste associations (e.g. *salt*, *honey*).

Motion simulations during language comprehension have been demonstrated with fMRI. Activations to motion language have been found in the motion sensitive area V5, which is involved in the visual analysis of motion. Saygin, McCullough, Alac, and Emmorey (2010) found V5 activation to both motion and fictive motion sentences compared to static sentences in a semantic sensibility judgment task. Rueschemeyer, Glenberg, Kaschak, Mueller & Friederici (2010a) also found V5 activation for motion sentences (motion described as moving in all directions except motion away from the observer) using a semantic anomaly detection task. That V5 activations were not observed for motion described as moving away from the observer suggests that motion simulations might occur only for motion relevant to the self (see Chapter 5 for similar discussion). There is however other studies that fail to find V5 activations to motion language (see Gennari, 2012 for review), but rather observe posterior middle temporal gyrus (PMTG) activations. PMTG is an area anterior to V5 and thought to include more schematic motion representations or more general action and event structure knowledge (Gennari, 2012). For example, Kable et al. (2002) found V5 and PMTG activations to images of objects in motion, but found only PMTG activations to motion words. Using a similarity judgment task, Bedny, Caramazza, Grossman, Pascual-Leneone and Saxe (2008) found no V5 activation but found differences between nouns and verbs in the PMTG. Such results suggest that motion simulations created in language comprehension do not include the specificity found in actual visual perception (Gennari, 2012). Bedny, Caramazza, Pascual-Leneone and Saxe (2012) found there was no difference in performance on a semantic similarity task to action verbs between blind and sighted individuals and that the functional profile and location of activation to these words did not differ between the groups. This seems to suggest that visual information is not critical to action verb meaning. In addition the left middle temporal gyrus was activated more to all verb types compared to nouns, suggesting that it may contain abstract verb representations rather than visual motion information. If visual information is not crucially recruited during the processing of visual language, then this would be evidence against embodiment and could mean that previous effects were epiphenomenal. However, psychophysical evidence for the recruitment of low-level visual processes in motion language does exist (Meteyard et al. 2008), as discussed above in Section 2.2. Further, it should be noted that a lack of support for embodied simulation should not be seen as support for amodal representations of meaning (Lebois et al., 2014). In addition, as discussed throughout this chapter, embodied effects are dynamic and context-dependent and these findings may simply reflect this.

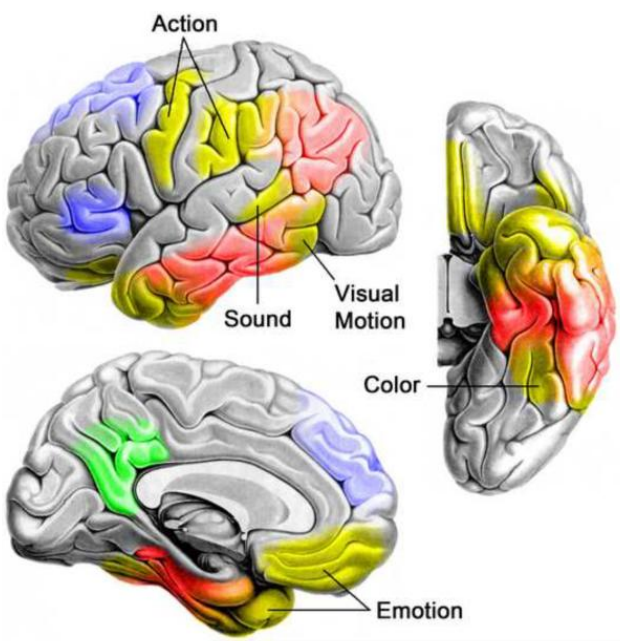


Figure 2-1. A neuroanatomical depiction of modality-specific regions recruited in language comprehension. Taken from Binder & Desai (2011)

2.3.3 Specificity

Activations in modality-specific regions can reflect very specific aspects of meaning. Activations in the motor system can be modulated by specific kinematics associated with the word. Areas more active to action words than abstract words showed a graded effect of activity based on action specificity, with more specific actions having greater activation (van Dam et al., 2010). For example, *to wipe* has a more specific motor plan than *to clean.* Action activations are also somatotopic (or effector-specific), with activations to words describing actions with specific effectors following the somatotopic organization of the motor cortex for real-world actions with specific effectors (Hauk et al., 2004). For example, activations to the word "to kick" activate similar regions of the motor cortex to those involved in producing a leg movement. Rueschemeyer et al (2010b) further investigated motor activations to object words by looking at the specific way that objects can be manipulated. Objects that need to be picked up to be used e.g. *cup*, *pen* (manipulable objects) activated frontoparietal sensorimotor areas more than objects that need to be picked up to be moved e.g. *bookend*, *clock* (volumetric objects).

Motor simulations are also sensitive to 'body-specificity' (Casasanto, 2009; see Chapter 1 section 1.4.5.). That is, the type of bodily experience the comprehender themselves has. Willems et al. (2010) found that right-handers activated the left premotor cortex in response to action words, whereas left-handers activated the right premotor cortex in response to the same words. It has also been shown that athletic experience can affect comprehension of language about action. Activations within the premotor cortex to language describing actions performed during ice hockey (e.g. *The hockey player held on to the puck*) were shown to be greater for participants that were experienced ice hockey players compared to novices (Beilock, Lyons, Mattarella-Micke, Nusbaum & Small, 2008; Lyons, Mattarella-Micke, Cieslak, Nusbaum, Small & Beilock, 2010) but no differences between ice hockey players and novices were observed for language about non-expert actions performed every day. Differences even existed between those with experience simply of *watching* ice hockey and those that were ice-hockey novices. This is strong evidence that semantic representations are built from people's sensorimotor experience: the comprehenders simulate the meaning of an action in a way that they would typically perform that action.

2.3.4 Simulation over imagery

Alternative explanations for brain activations observed during language processing are that they reflect explicit mental imagery processes rather than implicit mental simulations. At first blush the two processes appear difficult to tease apart. Mental simulation could be an unconscious version of mental imagery, or both could belong to a continuum that varies in richness of detail, with mental simulation being a more schematic version of mental imagery (Willems et al., 2009). Data from Willems et al (2010) suggest that mental imagery and mental simulation are two distinct processes. Participants either made lexical decisions to action words or were asked to actively imagine the word's corresponding action with their eyes closed. Both tasks led to activation within motor areas but the specific areas differed between the two tasks with no areas of overlap, suggesting that they are separate processes. The authors speculate that the distinction reflects the different functions of mental imagery and mental simulation. Mental simulation during language processing serves a predictive function: simulations are 'pre-enactments', preparing for future actions be it a physical response or a linguistic response. Mental imagery instead is a reflective process involving an effortful recollection of previous experiences.

To investigate whether sensorimotor activations during word comprehension reflect meaning or mental imagery, Hauk, Davis, Kherif and Pulvermüller (2008) looked at the effect of word frequency on category-specific activations. Word frequency is a lexical feature and as such should have no effect on mental imagery processes. For example, there should be no difference in mental effort needed to form a mental image of synonyms that differ in word frequency, such as 'baby' and 'infant'. Moreover, research has shown that word frequency plays a role in early word recognition processes (e.g. Allen, Smith, Lien, Grabbe & Murphy, 2005), and word frequency effects have been observed with EEG within 200 ms of stimulus onset (e.g. Hauk & Pulvermüller, 2004), much earlier than mental imagery would be observed. Word frequency was negatively correlated with activation in the left fusiform gyrus for visually related words and in the left middle temporal gyrus for action related words. Since word frequency reflects lexico-semantic processes, this is evidence in support of sensorimotor activations in meaning and not mental imagery: there is no explanation for why word frequency would correlate with mental imagery. It is important to note however that activations to motor-related words that correlated with word frequency were found in the left middle temporal gyrus and not within the motor cortex, as might be predicted based on previous results (e.g. Hauk et al. 2004). The middle temporal gyrus is thought to be involved in action observation (Aziz-Zadeh et al., 2006) and knowledge of biological motion (Martin, Wiggs, Ungerleider & Haxby, 1996). It is possible then that the simulations for motor-related words are perceptual rather than motoric (i.e. simulations of the perception of a motor event and not participation in that event). However, the motor-related items used in the study were rated on 'general action-related aspects' and which could have led to large variability in terms of activation between items making it difficult to detect effects in motor areas.

Further support for simulation over motor imagery is found in Revill, Aslin, Tanenhaus and Bavelier (2008). Activations occurred in motion sensitive regions during presentation of non-motion words that had motion cohort competitors. Participants were trained in an artificial language in which cohort pairs differed only in their final syllable (e.g. *biduko goti* vs. *biduka goti*). Semantic similarity was manipulated and words could refer to either change of motion or change of direction. Activation in regions of interest within MT/V5 was higher when a word's cohort competitor was a motion word compared to when it was a non-motion word. That is, the semantics of a cohort competitor affected levels of activation during the temporarily ambiguous period of word recognition. Activation of cohort competitors is thought to be an unconscious process so it is unlikely that such activations are due to conscious imagery of the competitor.

2.3.5 Context effects

A common question about the activations observed during comprehension is whether they reflect simulations of the meanings of individual words, or, in the case of sentences, simulation of a full event (e.g. Raposo et al., 2009). Reading single words, phrases or sentences is unlikely to capture processes involved in global coherence building or maintenance (Kurby & Zacks, 2013) that are required in reading longer discourse. There is evidence that activations observed during sentence comprehension reflect an overall simulation of the described event, or situation model, and not simply activations to the single words in a sentence. Boulenger et al. (2009) found stronger somatotopic effects in a late time window that occurred after sentence offset reflecting sentence level processing instead of single word processing, compared to an earlier time window, thought to reflect single word processing.

As suggested in Section 2.5, the amount of sensory and motor activation may depend on the depth of semantic processing that occurs, so we may expect there to be differences in simulation between single words, sentences and narratives. Simulations may be more likely for narratives since they are closer to mental imagery (Meteyard et al, 2012). One study has investigated patterns of activation to motor, visual and auditory events as described in larger discourse (Kurby & Zacks, 2013): short narratives from a fictional book. Clauses within the text were normed by a separate set of participants and coded by the authors as to whether they elicited auditory imagery (descriptions about sound, for example "*They sighed*"), visual imagery (descriptions of visual scenes e.g. "*Susan stood leaning against a nearby tree")* or motor imagery (descriptions of action e.g. "*she ambled over behind them*"). Results found that clauses with high auditory imagery activated areas within secondary auditory cortex and clauses that implied high motor imagery activated secondary somatosensory and premotor cortex. No increased activations were found to high visual imagery, but this may reflect the concurrent visual demands of reading, or alternatively that visual imagery remained quite consistent across all clause types (c.f. dominance of visual experience in Chapter 5). This type of evidence is crucial to embodied theories as it shows that activations can be observed with more naturalistic language stimuli that have not been specifically designed for an experiment with the aim of encouraging certain types of modality-specific activations. In addition, the larger discourse was read in a more natural manner: the participants could simply read the paragraphs and comprehend with no larger reading goal, building an overall event representation instead of having task demands such as explicit judgments about the stimuli, that may encourage sensorimotor activations. The study included an additional condition in which clauses were presented in a scrambled manner. Activations were stronger in the coherent narrative condition than the scrambled condition suggesting that mental simulations increase with a coherent mental model. Although this may seem to be at odds with evidence elsewhere where activations have been observed with single words and short phrases that are not presented in sentences or narratives, here the emphasis is on *coherence*. Single words and phrases are not incoherent.

Inconsistency within the imaging literature leads one to question whether mental simulations are fixed, static representations or instead are dynamic and flexible. Rueschemeyer, Brass and Friederici (2007) failed to observe action activations to complex verbs that included a motor stem compared to complex verbs that were built on abstract stems. For example, no difference was observed between words such as *begriefen* (to comprehend), which is built upon the stem *griefen* (to grasp), and a word such as *bedenken* (to think), which does not have a motor stem. Raposo et al. (2009) found activation for single motor verbs and for action sentences but did not find activation for motor verbs in idiomatic phrases (e.g. *kick the bucket*) (but see Boulenger et al. 2009, section 3.1). These studies suggest that sensorimotor activations depend upon both the morphological context and the sentence context of the word, and are therefore flexible and context-dependent rather than fixed and automatic. This view is incompatible with traditional perspectives on semantics that assume (often implicitly) that concepts are represented as situational invariant, having conceptual stability (Hoenig, Sim, Bochev, Herrnberger & Kiefer, 2008)

Both Rueschemeyer et al. (2007) and Raposo et al. (2009) used stimuli for which the motor component was not a critical part of the intended meaning. van Dam, van Dijk, Bekkering & Ruseschemeyer (2012) therefore investigated whether flexibility in embodied representations can be observed when the motor component is crucial to meaning, by manipulating the context in which a word appeared. Participants listened to words that had strong action and colour associations (e.g. *tennis ball, boxing glove*) while completing a go/no-go task in which they had to respond to either words denoting objects associated with the colour green or to words associated with actions involving the foot. Results showed that motor areas were activated strongly when the task required thinking about action properties, but not when it required thinking about colour properties. In a similar vein, Hoenig et al. (2008) found that modality-specific features are dynamically recruited depending on contextual constraints and relevance to the concept. Activations within modality-specific areas increased when participants had to decide whether a non-dominant attribute (e.g. *elongated* for *knife*) matched a target word compared to when they judged whether a dominant attribute (e.g. *to cut* for *knife*) matched the target word. Less accessible attributes lead to the highest activity because they are not a part of the dominant, core meaning of the concept.

Proponents of more disembodied views may present the lack of consistency in activations as a problem for embodied theories. Yet carefully assessing the contexts in which activations are observed and those in which they are not provides evidence for the flexibility of simulations. This flexibility is extremely intuitive. See Figure 2 taken from Hoenig et al. (2008) depicting how modality-specifically features are recruited dynamically dependent on task.

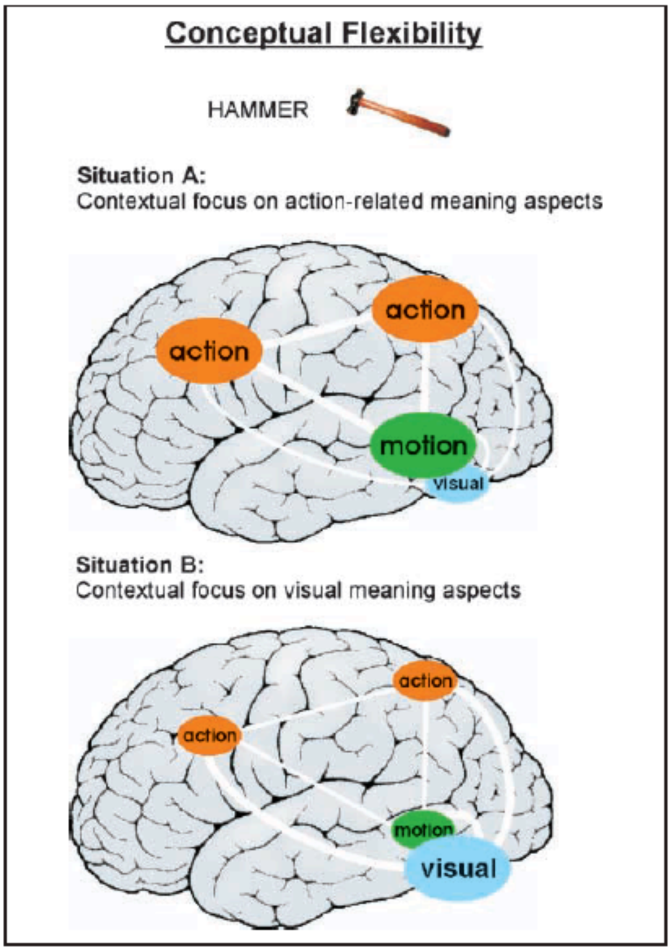


Figure 2-2. Flexibility in modality-specific activations. Taken from Hoenig et al. (2008). A depiction of how modality-specific regions (visual, motion, and motor) could be recruited dynamically depending on task context. The size of the ovals represents the contribution of the modality-specific regions under two different task contexts.

Using fMRI has provided evidence that brain regions involved in perception and action are activated during comprehension of language describing perception and action. Further, studies have revealed that these activations can be quite specific in terms of the effectors used in the action (Hauk et al. 2004), the types of actions described (van Dam et al., 2010) and the bodily experiences of the comprehender. As with behavioural studies, the activations observed across studies vary with context including depth of processing (Kurby & Zacks, 2013) and task specifics (van Dam et al 2011), and these effects need to be clearly defined and predictable (Zwaan, 2014). Much support for embodied theories comes from fMRI data, however it does not provide support for a crucial role of perception and action systems in meaning because the data are correlational and therefore support using other methodologies is required.

2.4 Electroencephalography (EEG)

One way to determine whether embodied effects are due to mental simulation or to mental imagery is to look at the time course of the effects. Embodied simulations are thought to be fast and automatic whereas mental imagery is more of a slow and deliberate process (Hauk et al., 2008). Importantly, if mental simulations are critical to understanding then they should take place within the time window of typical semantic processing. Using electroencephalography (EEG) one can measure event-related potentials (ERPs) online, providing important time course information related to cognitive processes. ERPs are electric potentials that reflect brain activity, time-locked to an event.

EEG has been used to demonstrate differences between word types at very early onsets. Kiefer et al. (2008) found an early onset of ERP activity within the left posterior superior temporal gyrus and middle temporal gyrus (around 150ms after word onset) when participants made lexical decisions to words with auditory associations, suggesting that access to auditory information during word comprehension is rapid. Hoenig et al. (2008) found ERPs reflecting interactions between word category (artificial vs. natural objects) and attribute verification type (visual vs. action-related) that were observed as rapidly as 116msec after word onset, reflecting early access to relevant visual and action features.

Action specificity is also an early effect. Hauk, Shtyrov and Pulvermüller (2008) monitored brain activity in fronto-central areas using EEG while participants silently read face-, arm- and leg-related actions. They specifically focused on the time range of 210-230ms, which was the time in which fronto-central areas became active. This time period reflects lexico-semantic access. Later periods (after 300ms) are thought to reflect post-lexical processes such as context integration. Results showed a significant word type by topography interaction. Left frontal areas had more activation to face words than legs words, whereas central sites showed more activation to leg words than to face words. Arm words had more activation than face words at the right central and right frontal sites and face words activated left prefrontal areas more than arm words. Thus, significant differences between categories of actions were demonstrated from around 220ms after stimulus onset within regions involved in actual movements and observation of movements.

Aravena, Hurtado, Riveros, Cardona, Manes and Ibáñez (2010) were the first to provide evidence of the 'bidirectional hypothesis' with what they call a 'neural signature of the action-sentence compatibility effect'. The bidirectional hypothesis proposes that comprehension of action language and motor processes share the same neural resources with mutual facilitation. That is, motor processes can effect language processing and conversely, language processing can effect motor processing. This is important to show that motor activation during comprehension is not simply an epiphenomenal effect or imagery effect occurring after comprehension and to demonstrate what they define as a "genuine and ongoing brain motor-language interaction" (Aravena et al., 2010). Participants listened to sentences describing actions using an open hand, closed hand or no action at all and indicated once they had understood the sentence. To respond, participants had to either press a button with an open hand or a closed hand making the characteristics of the response compatible or incompatible (or neutral) with that described in the sentence. The incompatible group exhibited an N400-like response (most often found with semantic anomalies) around Cz (the centre of the scalp), indicating a possible effect of the incompatible action response on sentence processing. For the compatible group, an enhanced re-afferent potential (RAP) was found. RAP is an index of movement-related sensory feedback to primary sensory-motor cortex, suggesting that information from the sentence facilitated the action response. Additionally, enhanced motor potential (MP) amplitude was found for compatible sentences. MP has been associated with speed and precision of movement and this increase again suggests facilitation from the compatible sentence context. Overall the results show an effect in the motor-to-semantics direction (N400) and in the semantics-to-motor direction (MP and RAP).

Boulenger et al. (2008) used EEG to investigate whether subliminally presented words affect motor planning. They focused on readiness potential (RP) which is a well-known indicator of motor preparedness, thought to arise from premotor and primary motor areas. Participants were subliminally presented with action words and concrete words while preparing for a reach and grasp movement. EEG recordings showed a significant reduction in RP amplitude for action words compared to concrete nouns following presentation of the masked word. Therefore, unconsciously processing action words during movement preparation had a stronger effect on motor processes than when unconsciously processing concrete words, and this difference occurred very soon after word onset. This is evidence that action activations are automatic and not produced by explicit processes.

Thus, EEG investigations have provided evidence that sensorimotor activations are very early and do not occur post-comprehension. Despite the high temporal resolution, EEG does not provide source localization with millimetre precision. Stronger evidence for the involvement of particular regions in meaning processing would come from the combination of ERP studies that have high temporal resolution with methods such as fMRI that have high spatial resolution (Hauk et al., 2008).

2.5 TMS

Despite the supporting evidence collected so far, some critics might argue that since methodologies such as fMRI are provide correlational evidence, results could still be explained by ‘disembodied theories’ where the observed patterns are due to spreading activation between language areas and sensorimotor areas (Mahon & Caramazza, 2008). This view suggests that sensorimotor activation found in all experiments could be merely epiphenomenal and not play a functional role in language comprehension.

Evidence is needed to tell us whether particular brain regions are critical to language comprehension or merely coactivated with it. Transcranial magnetic stimulation (TMS) is a method that can address this issue. TMS is a non-invasive technique with reasonable spatial resolution that when applied can temporarily alter the neuronal activity at specific locations in the brain and can thus assess a causal role for sensorimotor regions in language comprehension.

2.5.1 Modulating neural activity

After applying TMS to regions of interest one can look at the effect this stimulation has on comprehending or producing words or sentences of a specific category. If semantic processing is affected by the disruption of the corresponding sensory and motor areas then the affected areas must be a necessary part of semantic representation, and not epiphenomenal. This technique is often referred to as a reversible or virtual lesion (Tremblay, Sato & Small, 2012). These 'virtual' lesions can be more revealing than real lesions because they are induced at precise locations at a fine spatial grain and are not affected by other factors (such as brain plasticity) that can co-occur with real lesions (Tremblay, Sato & Small, 2012).

Pulvermüller, Hauk, Nikulin and Ilmoniemi (2005) delivered single pulse TMS below motor threshold (i.e. below the threshold needed to produce actual movement) to hand and leg areas of the motor cortex while participants completed a lexical decision task on hand and leg action words. Participants had to decide whether a presented word was a real word or not and responded via a quick lip movement, recorded with EMG electrodes to avoid any interference between a hand action response and the meaning of the word. An interaction between stimulation site and word type was observed with faster responses to arm words than legs words with TMS to arm areas and faster responses to leg words than arm words with TMS to leg areas. No difference between word types was observed when TMS was delivered to the right hemisphere (the non-language dominant hemisphere) or when sham TMS was delivered. The authors suggest that facilitation was observed due to the asynchrony between the onset of the word and the TMS pulse. TMS was delivered 150ms after word onset, thought to roughly correspond to the time at which meaning information is accessed (Sereno & Rayner, 2003). This timing is comparable to the effect of semantically related words in semantic priming experiments.

Cattaneo, Devlin, Salvini, Vecchi and Slivanto (2010) used rTMS (repetitive TMS) to the ventral premotor cortex (PMv) to disrupt semantic priming. rTMS produces longer lasting-lasting effects than single-pulse TMS and modulates cortical excitability to either improve or impair performance on cognitive tasks. Participants were primed with the word “animal” or “tool” before seeing another word from either category and decided whether it was a tool or an animal. Typically, participants responded faster on congruent than incongruent trials: faster when the category of the second word matched the word they were primed with than when it did not. However, when rTMS was delivered to the PMv this priming effect was reduced, but only for tools. Using a similar paradigm but matching short sentences with words that were similar or not in meaning, Tremblay et al. (2012) found that rTMS to the PMv removed the priming effect for sentences describing manual, object-oriented actions, but not for sentences describing visual properties of manipulable objects. TMS also removed differences in accuracy between congruent and incongruent trials for sentences describing manual actions as well as shifting sensitivity (d’) and response bias. Thus, the PMv plays a crucial role in understanding tool words and sentences about manual actions. However, this task did require an explicit judgment to be made and so some form of post-lexical imagery cannot be ruled out.

rTMS has also been used to test the Body Specificity hypothesis (Casasanto, 2009; see Chapter 1 section 1.4.5.) that proposes that mental simulations during action language processing should be different for different bodies (Willems, Labruna, D’Esposito, Ivry & Casasanto, 2010). rTMS was applied to the premotor area of the dominant hand during a task in which participants had to distinguish between verbs and pseudowords. Task performance was significantly reduced during rTMS for manual action verbs but not non-manual action verbs. This corroborates the finding that premotor cortex activation to action words differs according to handedness (Willems et al., 2010).

It is important to note than although we do see effects of virtual lesions, participants are still able to correctly respond to the words and sentences (Tremblay et al., 2012). There are many other aspects of features that make up the meaning of a word or a sentence that comprehension can still rely on (i.e. meaning is multimodal). Thus the effected regions are a crucial part of the comprehension process but may be utilized more in some situations than others (e.g. to reduce ambiguity) (Tremblay et al., 2012).

2.5.2 Measuring neural activity

TMS can be used to modulate neural activity and to measure neural activity in the motor cortex. By recording the size of motor-evoked potentials (MEPs) from the periphery muscles one can measure the excitability of the motor cortex. Oliveri et al. (2004) applied paired-pulse TMS to the hand area of the motor cortex and found that action-related words led to a greater activity in the motor cortex than non-action words. Interestingly, this facilitation was independent of grammatical class: both action verbs (e.g. *to throw*) and nouns referring to manipulable objects (e.g. *the key*) led to facilitation compared to non-action related verbs (e.g. *to belong*) and nouns (e.g. *the cloud*). Moreover, this facilitation was observed for a task that was designed to minimize activation of the meaning of words by focusing on word morphology only: participants were instructed via symbols to produce either the singular or plural version of presented word. Similar studies using this method have shown effector-specificity in the motor cortex for hand and foot related sentences (Buccino et al., 2005) as well as abstract action sentences (Glenberg, Sato, Cattaneo, Riggio, Palumbo & Buccino, 2008).

Gough, Campione and Buccino (2013) further investigated the specificity of motor cortex involvement in word meaning by looking at effects at the level of specific muscles. They applied TMS to parts of the primary motor cortex that control the extensor communis digitorum (EC) and the first dorsal interosseous (FDI) muscles

150ms after participants were presented with words. The EC muscle is involved in avoidance, releasing movements of the hand and the FDI muscle is used for approach and grasping actions of the hand. The words could be adjectives describing object properties relevant for approach behaviour and manipulation (positive), such as *soft*, or relevant for avoidance behaviour and releasing actions (negative), such as *filthy*. An interaction between adjective type and stimulation site was found, driven by a significant difference between MEPs recorded at the EC and FDI muscles for negative adjectives: MEPs at the EC muscle decreased and MEPs at the FDI increased relative to baseline. When the adjective implied an action that involved a specific muscle, MEPs at that muscle site decreased, suggesting interference between TMS and language processing. This is seen as strong evidence for embodied theories that cannot be explained by amodal theories, or 'secondary embodiment' (Mahon & Caramazza, 2008) for two reasons. First, since the adjectives were presented in isolation the results are hard to explain in terms of motor planning or motor imagery. Second, TMS was applied 150ms after word onset, which is too fast to affect post-comprehension associative processes.

By applying TMS directly to areas hypothesized to play a role in mental simulation evidence for their necessity has been provided. Further, TMS has been used to measure brain activity showing that language can increase excitability in sensorimotor regions. In sum, this methodology has provided evidence against a view of sensorimotor simulation as epiphenomenal and instead shown that it is a crucial part of comprehension.

2.6 Patient Data

As with TMS data, direct evidence against the view that simulations reflect mental imagery and are not crucial to comprehension, comes from studies in which deficits in motor or sensory processing result in a selective deficit in language processing of the same category. If the sensorimotor systems play a critical role in semantic representation, then damage to these areas should disrupt semantic processing of the same word types. Testing comprehension in patients with damage to sensory and motor areas therefore provides a crucial test for embodied theories. A completely disembodied approach would predict no effect of such damage on any type of language comprehension because language, perception and action are separate systems.

Most existing research of this nature has looked at patients with impairments in planning and executing actions, for example patients with lesions to areas of the brain involved in motor production (e.g. Neininger & Pulvermüller, 2003), patients with motor neuron disease (e.g. Bak, O'Donovan, Xuereb, Boniface & Hodges, 2001) and patients with Parkinson's disease (e.g. Boulenger, Mechtouff, Thobois, Broussolle, Jeannerod & Nazir, 2008; Fernandino, Conant, Binder, Blindauer, Hiner, Spangler & Desai, 2012).

Bak et al. (2001) investigated language comprehension and production in patients with motor neurone disease (MND), a disease that predominantly affects motor functions. Comprehension and production of verbs was found to be significantly more impaired than nouns for MND patients but not for healthy controls or patients with Alzheimer's disease (AD) who have both semantic and syntactic language impairments. This selective deficit in the MND patients suggests that the processes underlying verb representation is strongly related to those of the motor systems. Grossman, Anderson, Khan, Avants, Elman and McCluskey (2008) found that the degree of cortical atrophy in motor and premotor areas correlated with performance on action-verb judgments. In a similar vein, Boulenger et al. (2008) examined the effect of Parkinson's disease (PD) on the processing of action words relative to concrete nouns. Using a masked priming paradigm, it was found that priming effects for action verbs varied as a function of Levodopa uptake. Levodopa restores the function of the basal ganglia, improving the motor impairment in PD. When patients were off treatment (i.e. most severe motor impairment), no priming effect was found for action verbs, although there was an effect for concrete nouns. This is evidence that processing action words depends on the integrity of the motor system. It is important to note that overall performance on the lexical decision element of the task did not differ between verbs and nouns, only the priming effects. The subtle deficit might suggest that the role of the motor cortex in action word processing is relatively small.

Many studies with patients have not explicitly distinguished between nouns and verbs, and actions and objects so it is unclear whether the results reflect a problem with conceptual knowledge or grammatical knowledge (Oliveri et al. 2004). Both studies above used action *verbs* and concrete *nouns*, thereby confounding grammatical class with semantic category. Fernandino, et al. (2012) removed this confound by testing Parkinson's patients and age-matched healthy controls on action verb and abstract verb processing. They found that compared to healthy controls, patients performed much worse with action verbs than abstract verbs, indicating that Parkinson's disease leads to problems with processing action language rather than problems processing verbs. In addition, two tasks were used, testing action comprehension at early automatic stages (lexical decision) and under explicit semantic processing (semantic similarity judgments). Differences between patients and controls were observed with both tasks, suggesting that the effect of the motor system occurs both during shallow, automatic tasks and deeper more controlled tasks.

Overall, the results of the above studies seem to falsify a 'disembodied' hypothesis that allows no interaction between language and perceptual and motor systems. The studies also seem to suggest that neither can we accept a strong form of embodiment which would predict an 'all or nothing' contribution of motor processes. That is, patients' comprehension of the problematic semantic classes is not completely lost, but rather hindered. It remains an open question as to the nature of action concepts in patients with compromised motor systems or brain lesions. However, one should also keep in mind that the meaning of a word contains information from more than one modality and as such, deficits in only the motor component would not make word recognition impossible. For example, the word "kick" is likely to contain visual and auditory information about what it is like to perceive oneself or others kicking, not simply motoric representations. The involvement on different sensorimotor domains in simulations is explored in Chapters 5 and 7 of this thesis.

The type of task adopted is important in these investigations. It is questionable as to whether a task that does not depend on deep semantic analysis would be sensitive to conceptual deficits. Some argue that lexical decision tasks do not in fact involve semantic analysis and is therefore not the best tool to investigate comprehension difficulties (Mahon & Caramazza, 2008). More sensitive tasks such as lexical decision with priming (Boulenger et al. 2008, Fernandino et al. 2012), or tasks that require more explicit semantic analysis such as semantic similarity judgments (Fernandino et al. 2012), may be necessary.

2.7 Summary

There is now a broad literature providing evidence for the simulation of many semantic features across different methodologies. Behavioural experiments that combine language with sensorimotor stimuli or tasks, as well as fMRI experiments that measure BOLD response during word and sentence presentation have found evidence for the simulation of action, visual, auditory, gustatory and olfactory features. At present, evidence exists for simulations when processing both words and sentences, yet a comparison between the nature of the two types of simulations has not been completed. Some initial evidence suggests that the temporal dynamics of the simulations may differ (Boulenger, et al., 2009).

The simulations used in comprehension are not basic, schematic reenactments of experience, but are detailed and include a high level of specificity. Simulations are specific to the effector used in an action (Hauk et al., 2004), the muscles used in an action (Buccino et al, 2005; Gough et al., 2013), specificity of an action (van Dam et al., 2010) and the body and personal experience of the comprehender (Cassasanto, 2009).

Against critical views, research has provided strong evidence that activations observed across experiments are due to mental simulations that are critical to comprehension and not the result of post-comprehension mental imagery. Simulations have been shown to occur early (Kiefer et al., 2008; Hauk et al., 2008; Gough et al., 2013), even for language not consciously perceived (Boulenger et al., 2008), they are sensitive to lexical frequency (Hauk et al., 2008) and cohort competitors (Revill et al., 2008) and have been shown to occur in separate brain areas to mental imagery (Willems et al., 2010). In addition, the disruption of sensorimotor regions with TMS (Pulvermüller et al., 2005; Cattaneo et al., 2010;

Cappa et al, 2002) or through degenerative disorders (Neininger & Pulvermüller 2003; Bak et al., 2001; Boulenger et al., 2008; Fernandino et al., 2012) causes problems with the comprehension of language about similar sensorimotor features.

In line with Barsalou, simulations are not fixed but appear to be flexible. Simulations are sensitive to factors such as depth of processing (Louwerse & Jeuniaux, 2008), grammar (Bergen & Wheeler, 2010) and literality (Rueschemeyer et al., 2007; Raposo et al., 2009), task (van Dam et al., 2012).

This chapter has provided a comprehensive review of research investigating embodied language processing and highlighted some key features in this evidence. This chapter serves at the foundations for the next chapter that specifically discusses the domain of investigation in this thesis and outlines the questions to be investigated.

Chapter 3 The Present Thesis

The aim of this thesis is to investigate how meaning in language is understood, specifically how language about *speed* is understood. I approach this topic from an embodied language framework, which posits that language comprehension involves the activation of relevant sensorimotor information and therefore uses some of the same neural systems as perception and action (as described in Chapters 1 and 2). In this chapter I introduce the topic of speed in language as well as time and space in language (which are components of speed) in order to demonstrate how such domains can be simulated and introduce some relevant experimental paradigms. I then describe the putative neural mechanisms involved in perception of speed and in producing speeded actions that will be implicated in the mental simulation of speed. Finally I introduce the content of each experimental chapter and what the results can reveal about the mental simulation of speed.

Previous research has provided support for embodiment of a number of features of action and perception, in addition to initial evidence for more abstract domains, as covered in Chapters 1 and 2. Speed is particularly interesting in this framework for several reasons. First, it integrates the dimensions of space and time, thus making it a more complex feature than those investigated so far. Speed is also a fine-grained dimension of an event. For example, when perceiving a motion event, one may simply perceive and encode that an object or agent is moving, and not automatically represent its speed (unless speed becomes relevant, such as when a car is approaching you). Speed may be even less relevant in language comprehension. For example to understand that an agent moved to a particular destination or along a particular route, one does not require a representation of the manner in which the motion event occurred for the fundamental meaning of the sentence to be understood. From research evidence so far it is unclear how much information from an event is contained in mental simulations (Sanford, 2008), what features are included in a simulation or at what grain information is represented. Since language comprehension is often time-pressured and occurs in noisy environments it could be the case that only salient features of objects or events are included, such as object shape, and not more fine-grained features that we experience in our daily interactions with the world. Since speed is a fine-grained dimension, it may not be salient enough, or important enough, to be a necessary component of mental simulations. For example, to understand that "*John went to the shop*", one may only need to simulate that there is an agent, a destination and a motion act, but not the manner, distance or duration of the motion event. The Immersed Experiencer Framework (Zwaan, 2003) and Perceptual Symbol Systems theory (Barsalou, 1999a) propose that mental simulations are schematic and do not contain all aspects of an event. Like real-world perception, attentional constraints limit how much information is attended to (e.g. Simons & Levin, 1997). Despite this schematicity, embodied theories still allow for finer grained distinctions in meaning than amodal theories do (e.g. Stanfield & Zwaan (2001): orientation, Winter & Bergen (2012): distance). However, it is still unclear at what grain information is represented in mental simulations and how closely they correspond to real world experience. Investigating the mental simulation of speed in language can therefore help to address these questions.

Before describing the specific research questions of the thesis, I will briefly summarize what is known so far about the contribution of perception and action systems to the comprehension of language about space, time (components of speed) and speed. This will introduce ways in which less tangible domains can be investigated: the types of questions that can be asked and the experimental paradigms that can address them, providing a foundation for the experimental chapters to come. I will then briefly discuss how speed in perception and action is represented in the brain, which will point to potential systems recruited in the simulation of speed.

3.1 Time, space and speed in language

Time, space and speed are domains that are relatively abstract in comparison to other domains such as colour and texture. We do not directly perceive them but infer them via other referents. Time needs a person to experience it, or it can be measured using a clock, but it does not exist without them. Space needs land or buildings or people for it to be defined. And speed needs the motion of an object. However, although we cannot really point to them, photograph them, or hold them, we do experience them all the time and we can measure them.

These domains are integral to our everyday lives and necessary in communication. Our entire day is organized around time: we are aware of what time we get out of bed, how long the work commute is, when our first meeting is and how long it will last. Time is always on our mind and thus always present in our topics of communication. Space is just as important: we need to know where we left the car keys, how far the walk to the venue is or from what platform the train leaves. Moreover, space is often described in language to direct other people to locations and objects and is thus very often mentioned in sentences. Speed may be less salient in our daily activities than space and time but still important in our interactions: for example, we might perceive that the train is pulling into the station extremely slowly, we might have to run to work quickly or cannot cross the road because a car is driving too fast.

The significance of each domain in our daily interactions suggests that they are often discussed in language and therefore their meaning needs to be salient and understood correctly. The successful comprehension of language about time, space and speed is particularly critical since the tracking of these domains can have important consequences (e.g. being late, walking into a large object or crossing a road in time).

Time is by far the most abstract of the three domains. Unlike speed and space, time cannot be directly perceived with the senses, so it is difficult to predict how it can be embodied in our perceptual systems during language comprehension. One way for time to be embodied is through metaphor (Boroditsky, 2000; Lakoff & Johnson, 1980, 1999). Time can be grounded in our perceptions of space and motion. These metaphors are extremely prevalent in our everyday talk of time. Examples include '*The afternoon raced by'*, '*Ski season is approaching'*, '*She has a bright future ahead of her'* (Nunez & Cooperrider, 2013). Sell and Kaschak (2011) tested whether time shifts in comprehension are represented spatially. Participants read sentences that described past and future events and had to make sensibility judgments (does the sentence make sense?). They responded by either moving towards or away from the body to press a button, or by pressing buttons that were towards or away from the body without moving. Responses to sentences describing future events were faster when participants had to respond away from the body compared to towards the body, and vice versa for sentences describing the past, but only when moving to give the response and only for long time shifts (e.g. a month). Thus, the concept of time is grounded in the simulation of motion towards and away from the body.

Evidence shows that temporal information is represented during discourse comprehension in the construction of a situation model (simulation) of the described event (Zwaan, 1996; Anderson, Garrod & Sanford, 1983). Zwaan (1996) manipulated the chronological distance between two described events to be short or long (e.g. *a moment later* vs. *an hour later*). Sentence reading time was found to be longer for greater narrative time shifts. Moreover, information from a previous event was more difficult to access when it was followed by a shift in time compared to when it was not. This suggests that the representations of the two events in memory are more strongly connected when they are not separated by a time shift.

Anderson et al. (2008) found that manipulating simple morphological information could change the duration of a simulated event. Participants' task was to place a character in the appropriate place in a scene according to the meaning of a presented sentence. Participants placed the character closer to the beginning of a to-be-used path and had longer mouse movement durations in completing the task when they heard a sentence with a past progressive (e.g. "*Tom was jogging to the woods and then stretched when he got there*") than a simple past tense (e.g. "*Tom jogged to the woods and then stretched when he got there*"). Thus, grammatical aspect influenced how the event was simulated; with a past progressive the event was seen as on going in comparison to a simple past tense where the event was seen as completed. Since the event was construed as on going the simulation was longer.

It is now well-accepted that language drives attention to spaces in the world, thus meaning in language must be grounded in our spatial representations of the world. Spatial language is thought to activate perceptual simulations that reflect the typical relations between objects (Coventry, Lynott, Cangelosi, Monrouxe, Joyce & Richardson, 2010). Early studies demonstrated that eye-movements towards reference objects are time-locked to incoming linguistic information (e.g. Allopenna, Magnuson & Tanenhaus, 1998). Features of motion can also be part of the perceptual simulations occurring during comprehension of spatial language. For example, it has been shown that when mapping a spatial expression to a visual scene, eye movements reflect motion characteristics if the described spatial configuration suggests motion: when viewing an image of a cereal box over a breakfast bowl and hearing a sentence such as "*The box is above the bowl*", participants spend more time looking at an area of the scene consistent with the direction in which the cereal will fall from the box (Coventry et al 2010). Spatial information in language directs attention to relevant spaces even in the absence of a visual scene: Spivey & Geng (2000) found that when participants listened to narratives describing movement in a certain direction, eye gaze was focused more on the corresponding area of a blank screen.

Spatial information is also activated in single word comprehension (Zwaan & Yaxley, 2003; Estes, Verges & Barsalou, 2008; Dudschig, Lachmair, de la Vega, de Filippis & Kaup, 2012). Zwaan & Yaxley (2003) found participants were faster to decide if two words were related if they were displayed in a spatial configuration that matched how the referents would appear in the world (for example '*attic*' above '*basement*') compared to the opposite configuration ('*basement*' above '*attic*'). Reading the words activated the spatial features of the objects and hence facilitated responses when the spatial location of the words on the screen matched them. When the word pairs were presented horizontally, no differences were found, ruling out any explanation of the results based on word order. Dudschig et al. (2012) similarly presented participants with nouns that did not explicitly convey spatial information in their meaning but whose referents are typically found to be high or low in the environment (e.g. *cloud* vs. *shoe*). Four seconds after word presentation a visual target (a filled white box) was presented above or below the central fixation and participants had to detect its presence. Target detection was significantly faster when the location of the target matched the location of the referent's typical location (e.g. target presented above fixation after the word *cloud*). Thus, although the word was irrelevant to the task, its spatial meaning affected attention on the vertical axis. Although spatial features of a word's referent have been shown to facilitate target detection, elsewhere they have hindered target identification (Estes et al., 2008). Estes et al. (2008) similarly presented nouns denoting objects with typical locations in the centre of the screen followed by a target above or below fixation, but instead of simply detecting the target participants were required to identify whether it was the letter *X* or *O*. Now performance on the task was worse when the referent of a word's typical location matched the location of the target. The words oriented spatial attention, as before, but now the perceptual simulations generated for the words' referents interfered with the identification of the target letter. Thus activation of spatial features from single words may assist or hinder a subsequent perceptual task depending upon whether the task requires detection or identification.

Speed has so far been fairly neglected in the investigation of embodiment, however a small number of studies exist that suggest that speed information is simulated during comprehension. Fecica & O'Neill (2010) investigated the simulation of speed in short narratives. Children listened to narratives one sentence at a time by pressing a mouse button. The narratives described the journey of a young boy to his aunt's house. Critically, the duration of the journey was manipulated by introducing the character as taking his journey either by walking (slow motion) or by car (fast motion). Children were found to take significantly longer understanding the sentences when the character was described as walking compared to driving. Additionally, when a psychological factor of the characters was manipulated, processing times were longer when the character was described as being less eager to take the journey compared to when they were eager (e.g. going to the dentist opposed to buying ice-cream). Thus comprehenders are able to use knowledge about the duration of events based on speed information inferred from the method of transport or motivation of the character, and take longer to simulate events that are typically slower. Related, Anderson, Matlock & Spivey (2010) found that the described terrain of a character's journey (hard or easy) affected the duration of a simulation. After to listening to sentences describing a journey (e.g. "*The road to the university was rocky and bumpy*" vs. "*The road to the university was level and clear"*), participants had to place a character in a corresponding visual scene and their mouse movements were tracked. Duration of mouse movements was found to be longer when the terrain of the journey was described as hard compared to easy (but only for past progressive sentences) reflecting how real-world movement would be slowed by difficult terrain.

3.1.1 Summary

This brief summary of work investigating time, space and speed in language has demonstrated how less tangible domains can be investigated from a simulation perspective. Simple reading or processing time can be used to assess the duration of mental simulations (Anderson et al., 1983; Zwaan, 1996; Fecica & O'Neill, 2010), which should differ between events of different speeds. Measuring eye-movements during comprehension allows the tracking of spatial and motion features that are simulated (Allopenna et al., 1998; Coventry et al., 2010), both of which are necessary in the simulation of speed. Another method of assessing simulation is by combining sensorimotor processing (e.g. action or spatial information) with language about the same sensorimotor information (Zwaan & Yaxley, 2003; Sell & Kaschak, 2011). If simulation takes place in systems of the brain used in sensorimotor processing then the combination should affect language comprehension. Moreover, the effect should be bidirectional, with language affecting judgments in other domains (Estes et al., 2008; Dudschig et al., 2012) including target detection (Duschig et al., 2012) and identification (Estes et al., 2008).

3.2 Speed in the brain

In order to investigate the representation of speed in language, it is important to consider how speed of motion and action is processed in the brain so that we can predict the mechanisms used in speed simulations during comprehension. Speed can be defined and processed in two fundamental but different ways. The speed of an object in motion can be *perceived* and the speed of one's own motor movement can be *planned* and *executed* (as well as perceived). One process involves perception and the other motor planning.

A large distributed network of neurons in the cortex is involved in the processing of a moving stimulus. In comparison to the encoding of *direction* of motion in the visual cortex, much less is known about the encoding of *speed*. However, the mechanisms underlying both are thought to be quite similar (Watamanivik & Duchan, 1991). Neurons encoding speed fire maximally for a stimulus at optimal speeds and speed is inferred by converting the response of a large population of neurons into a population code (Priebe & Lisberger, 2004). Firing rates to motion far from the optimal speed are significantly diminished (Maunsell & Essen, 1983).

There have been reports of speed processing in a number of areas of the visual cortex. Research into visual processing in the macaque suggests that 25% to 61% of cells in area MT are tuned for speed (Perrone & Thiele, 2001, Priebe, Cassanello & Lisberger, 2003). Recent research suggests that the human MT/V5 is similarly composed of a majority of speed-tuned neurons, as is V1, but to a lesser extent (although this has not been reported consistently). In an fMRI study, Lingnau, Ashida, Wall and Smith (2009) presented participants with drifting sine wave gratings dominated either by speed or temporal frequency and investigated whether responses weakened with repetition. Results suggested dominance for speed encoding in all visual areas but with weaker effects in earlier areas. A similar result has been found using single pulse TMS (Matthews, Luber, Qian & Lisanty, 2001). Whilst subjects made speed and direction judgments they were stimulated both medially and laterally to disrupt areas V1 and the hMT+/V5, respectively. Speed discrimination was significantly affected at both stimulation sites but more so for the medial location (V1). Using rTMS, McKeefry, Burton, Vakrou, Barret and Moorland (2008) similarly found the stimulation of hMT+/V5, as well as V3A, to disrupt speed processing but found no effects when stimulating V1. It has been suggested that speed tuning is first generated in V1 with later feedforward connections to MT (Priebe & Lisberger, 2004), however McKeefry et al. (2008) proposes that V1 may not crucially contribute to speed processing and motion signals may bypass V1 via the lateral geniculate nucleus (LGN) directly to MT. Studies with patients have shown that deficits in the perception of speed of moving objects (akinetopsia) occur with lesions in area hMT+/V5 (Barton, 2011), and transient akinetopsia has been demonstrated with TMS of area hMT+/V5 (Beckers & Homberg, 1992). In comparison to the other studies described however, these studies measure deficits according to subjective experience, rather than psychophysical measurements. Processing speed in the auditory cortex, although less well understood is thought to mirror that of the visual cortex. For example, in the primary auditory cortex of the cat, it has been shown that half of the cells are tuned for speed (Poirier, Jianng, Lepore & Guillemot, 1997).

The cerebellum has been shown to be involved in the control of speed of limb movements (Roitman, Pasalar, Johnson & Ebner, 2005). More specifically, the cerebellum represents the timing between successive events (Ivry & Spencer, 2004). Patients with lesions to the cerebellum have difficulty with the timing of motor events but are less impaired with smooth and continuous movement (Ivry & Spencer, 2004). The timing mechanism of the cerebellum is thought to extend beyond motor events to perception as well: patients with damage to the cerebellum are impaired in making velocity judgments but not position judgments about a visual stimulus (Ivry & Diener, 1991). The supplementary motor area (SMA) is also involved in motor activity with patients with bilateral SMA lesions experiencing akinesia and difficulty with spontaneous movement. Further, stimulation of the SMA results in the urge to move and firing rates of neurons in the SMA are inversely correlated with speed of hand movements (firing rate decreases as speed increases) (Tankus, Yeshurun, Flash & Fried, 2009). The basal ganglia may similarly be important for the timing of movement, as suggested by patients with Parkinson's disease (PD). PD is a neurodegenerative disease cause by a deficiency in the dopaminergic pathway from the basal ganglia leading to reduced activation in brain areas involved in motor planning and execution. PD patients are characterized by a range of motor problems including bradykinesia (slowness of movement) and rigidity.

To summarize, a large part of the visual cortex is tuned to process speed of motion, although some discrepancies between studies exist in terms of whether this includes early stages of processing (e.g. McKeefry et al., 2008). It is assumed that the processing of visual speed is mirrored in the auditory cortex for auditory speed. In terms of producing fast and slow movements, the cerebellum and basal ganglia are likely to be critical, both having roles in timing information, and the SMA plays an important part in producing movements at different speeds.

The work described in this thesis aims to test whether understanding speed in language involves similar processes to understanding speed in the world and occurs via mental simulation. When comprehending language describing perceptual or motor aspects of speed, I expect that parts of the systems described above will be recruited in service of comprehension. My experiments test the proposed link between speed in language and speed in action and perception and attempt to reveal the underlying mechanisms and the nature of this relationship by combining language about speed with various conditions in which speed of action or perceptual stimuli is manipulated.

3.3 Description of experimental chapters

The following experimental chapters set out to find evidence for the mental simulation of speed in the comprehension of language that describes speed. Using different linguistic types (i.e. words and sentences) I can test to what extent the presence and nature of speed simulations differs for different linguistic contexts. For example, Bergen et al. (2007) argue that mental simulations develop only when the meanings of single words are integrated into a larger sentence structure and not for lexical associations of words alone. However, other studies (reviewed in Chapter 2) have shown that interactions between language and perception/action can be observed when processing single words as well. In addition, using a range of experimental paradigms and testing different subject populations provides a thorough investigation of the simulation of speed in language and the potential to define any factors (such as contextual factors) that influence the simulation of speed. Note that throughout the investigation, I will be using the term 'simulation' synonymously with all types of modality-specific activations. Some researchers may be of the opinion that 'simulation' only applies to the meaning of events (i.e. evoked by sentences) where activations from individual referents of words are integrated together. Activations to single words could be more appropriately considered as partial simulations. Here, the term 'simulation' refers to all modality-specific activations in response to linguistic stimuli. Below I describe each experimental chapter including a summary of the paradigms used and the fundamental research aims.

3.3.1 The influence of perceptual processing on speed word comprehension (Chapter 4)

If understanding words about speed requires the use of systems involved in real-world perception of speed, then combining speed words with speed perception should affect processing of those words to some extent. Based on this prediction, the experiments in this chapter combine perceptual speed of different modalities (auditory and visual) with a task on speed word comprehension (lexical decision task). These experiments investigate whether speed simulation can be found in single word comprehension, without any sentence context. In addition, by using perceptual stimuli of different modalities I can assess to what extent mental simulations for speed are multimodal, reflecting the importance of those modalities in real world perception. Further, I manipulate the modality in which the verbal stimuli are presented: as spoken or written words. With this manipulation I can test whether the modality of perceptual stimulus and the modality of the linguistic stimulus affect the nature of mental simulations. Finally, by using perceptual speed stimuli that are more or less related to real-world sounds (for example, abstract sounds like white noise, or real-world sounds like footsteps) I can test whether speed simulations include information about specific agents in motion or if instead whether speed information is abstracted away from an agent.

3.3.2 The influence of speed words on perceptual processing (Chapter 5)

If the combination of perceptual speed and speed words affects comprehension of speed words, then the converse should also be true: comprehending speed words should affect the perception of speed. To investigate the two-way relationship between speed word processing and processing perceptual speed, this chapter investigates whether listening to speed verbs affects how visual speed is perceived. Using a psychophysical task I test the effect of listening to fast and slow speed words on psychophysical measures of speed discrimination for visual stimuli moving at different speeds. Participants listened to spoken speed words while completing a visual speed discrimination task in which they judged whether moving sine wave gratings were moving faster or slower than a standard moving grating. Speed discrimination threshold (how easy it is to discriminate between different speeds), point of subject equality (perceived speed of the standard) and reaction time were measured. Effects of speed words on measures of speed discrimination threshold would suggest that the interaction between speed in language and speed in visual perception is occurring at low levels of perception. If instead effects are observed in point of subjective equality, the interaction would take place at levels of bias. By using this psychophysical paradigm I can test the boundaries of embodied effects for speed language, assessing at what level of perception speed simulations occur.

3.3.3 The influence of speeded actions and perceptual speed on comprehending sentences about fast and slow events (Chapter 6)

The experiments in this chapter follow the rationale of those of Chapter 4 and test whether sensorimotor speed can affect comprehension, focusing now on comprehension of sentences about speed. The first experiment manipulates auditory speed and the second manipulates speed of action. By adding a motor component to the investigation I assess whether moving quickly or slowly affects responses to sentences about fast and slow motion. Further, the sentences used here assess simulations for sentences about both fast and slow full-body actions as well as sentences about fast and slow actions performed with the hands. This means I can test the specificity of the effect of perceptual speed and speed of action on sentence comprehension (i.e. whether or not the simulation includes information about the effectors used in the actions). This chapter also adds to the investigation by assessing speed in both verbs and adverbs. Verbs and adverbs occur at different points in a sentence which means that speed information is accessed at different points: for verbs, speed is tied to the action in the same word, however for adverbs, speed information is separate to and comes before the verb of action. Thus, the nature of speed simulations when speed is encoded in a verb versus an adverb may differ.

3.3.4 Eye movements and the mental simulation of speed in sentences (Chapter 7)

This chapter investigates the mental simulation of speed in sentences that describe fast and slow motion with verbs and adverbs, by measuring eye movements during comprehension. Spoken sentences were presented to participants whilst they viewed a visual scene that contained agents and destinations that were described in a sentence. Eye-movements towards these visual images were measured during sentence processing. This paradigm allows mental simulation to be monitored in real-time and in a more natural language setting than the previous sentence experiments described in Chapter 6. That is, mental simulation is not measured using an additional task or judgment about the sentences nor by combining sentence processing with other stimuli in order to produce interference/facilitation: participants simply comprehend the sentences naturally. Further, by manipulating the speaking rate of the presented sentences (fast or slow), and components of the visual scene (whether or not distractor destinations are present), I assess the effect of context on speed simulation.

3.3.5 Is speed processing in language affected by deficits in the motor system? (Chapter 8)

A crucial test of an embodied theory of speed is to test whether individuals with impairments in processing speed or who have movement disorders also have difficulty understanding speed in language. This final chapter investigates the comprehension of speed language in patients diagnosed with Parkinson’s disease (PD). Experiments use a range of language related to speed, including speed verbs and adverbs, as well as abstract verbs and adverbs, and address comprehension of speed language at various depths of processing (lexical decision, sentence sensibility judgments and semantic similarity judgments). Patients’ performance is compared with control subjects. Based on the patients’ motor deficits, the embodied approach would predict that they would have more difficulty processing all action verbs relative to abstract verbs and more difficulty processing words that describe fast speed compared to words that describe slow speed, because they have greatest difficulty in moving quickly. There should be no difference between word types for control participants. A disembodied approach would predict no such differences.

3.3.6 Summary of chapters

The research questions outlined above enable a full investigation of the mental simulation of speed during comprehension. Throughout the chapters, the issues in embodied research that were raised in Chapter 2 (features, specificity, mental imagery versus mental simulation, and context) are addressed. By investigating the simulation of speed I am exploring a fairly neglected feature in terms of embodiment, a feature that is more fine-grained than most in the literature. Looking at speed also sheds light on the question of specificity in simulations: speed information is not crucial to understand an event such as an agent moving to a destination, but for a simulation to accurately reflect real-world experience it should include this level of detail. Within the chapters I also explore speeded actions with both the whole body and with only the hands/arms and test whether or not the difference in effector is encoded in the simulation of speed. I also manipulate a variety of contexts, including linguistic type, match in modality of perceptual and verbal stimuli, components of a supporting visual scene and speaking rate of presented sentences, and assess how these manipulations affect the nature of any observed simulations. I also add to the debate between mental imagery and mental simulation by using eye-tracking and a task that does not require explicit judgments about the linguistic stimuli (and therefore unlikely to produce imagery effects). Finally, by testing comprehension of speed in language in PD, I assess whether or not speed simulation of actions is critical to comprehension of speed language.

3.4 Conclusion

The main aims of the experimental work in this thesis have been discussed and the planned experiments described. Overall, the work in this thesis adds to embodied investigations by addressing a more fine-grained feature of events, exploring the specificity of speed simulations, assessing the effect of a number of contextual factors on speed simulation and finally, providing a crucial test of the embodiment of speed by assessing comprehension of speed in language in patients with PD. Evidence from language about time and space suggest that speed simulations can be observed in reaction times for comprehension tasks and target detection and identification tasks as well as in eye-movements that are observed during sentence comprehension. I have briefly summarized evidence for the neural systems involved in the perception of speed and production of speeded actions. Parts of these systems should therefore be recruited in the simulation of speed. The remaining chapters of the thesis focus on the experimental investigation.

Chapter 4 Perceptual speed and lexical decision

In this chapter I test the embodiment of speed in single speed verbs. I chose to investigate speed verbs that denote fast or slow full-body movements (e.g. *dash*, *amble*) using an experimental paradigm that combines speeded perceptual stimuli (fast and slow) with a task that assesses comprehension of single words: a lexical decision task. In this task, participants are presented with single words and nonwords and have to decide if they are real words or not. Lexical decision is sensitive to a number of semantic variables including number of senses, imageability and body-object interaction (Yap, Pexman, Wellsby, Hargreaves & Huff, 2012) and should therefore be sensitive enough to reveal speed simulations. Further, this task does not require explicit access to the semantic variable of interest (i.e. speed) in order for a response to be made. That is, the judgments that participants make do not relate to speed or motion. This point is important to show that mental simulation is an automatic component of natural comprehension, rather than the result of conscious mental imagery or task-specific strategies (Mahon & Caramazza, 2008).

Participants were presented with a fast or slow perceptual stimulus followed by a word or nonword to which they had to respond. If understanding speed verbs requires processes shared with speed perception, then presenting speed words immediately after speeded perceptual stimuli should affect responses. If the mechanisms used to process the perceptual stimuli are active at the same time as, or immediately before they are required to process the words then there are two possibilities. First, since activation is currently devoted to processing the perceptual stimuli then there may be few resources available to process the words. The lack of resources would lead to deficient word processing (interference between perception and comprehension). Alternatively, the active or partially active state of the perceptual regions may boost processing of the word, leading to faster word responses (facilitation).

Similar paradigms have been used elsewhere for direction language (Meteyard et al., 2008, Kaschak, Madden, Therriault, Yaxley, Aveyard, Blanchard & Zwaan, 2005;

Kaschak et al., 2006). Response time for lexical decisions to direction verbs was hindered when participants concurrently perceived visual motion of a matching direction at near threshold levels (Meteyard et al., 2008), suggesting processes used in visual direction perception and direction verb comprehension overlap. Kaschak et al. (2005) describe a set of studies in which participants read or listened to sentences that described motion in a particular direction at the same time as viewing a dynamic visual display or hearing a directional motion stimulus (moving white noise). Facilitation effects were found for congruent conditions (the direction of the visual stimulus and the sentence matched) when the modality of the perceptual stimulus and the modality of sentence presentation matched. When the two modalities did not match responses were slower for congruent items. One account of the existence of both facilitation and interference effects is in terms of perceptual attention (Connell & Lynott, 2012b). Since the perceptual and attentional systems are strongly related, the amount of attention recruited by a perceptual stimulus is thought to influence the perceptual simulation process. For example, if visual attention is strongly occupied by a moving visual stimulus then there will be few attentional resources available for a visual simulation, leading to an interference effect. On the other hand, if a visual stimulus merely directed visual attention but did not continue to occupy it, it would lead to a facilitation of the simulation. According to an attentional explanation (Connell & Lynott, 2012b), in the present studies, facilitation effects would be predicted because the perceptual stimuli occur *before* the linguistic stimuli, and therefore would not occupy attention during simulation.

As well as testing the simulation of speed in single words, the experiments here have two further aims regarding the perceptual modalities used in speed simulations and the importance of the modality of presentation in the task, as described below.

4.1 Multimodal simulation

If understanding words activates sensorimotor information gained through experience, then a single word should produce activations across multiple modalities such as visual, auditory and action features, because these modalities work together continually through everyday experience. Real-world perception involves the integration of multiple sources of sensory information (Burr & Alais, 2006) and mental simulation can re-enact any perceptual aspects of experience distributed throughout modality specific areas of the brain (Barsalou, 1999a). For example, the experience of the concept *car* is likely to include the visual experience of seeing a car drive along a road from different perspectives, the auditory experience of hearing a car driving (e.g. engine revving, horn beeping) and the action of steering the wheel or pressing on the clutch. The concept could include less prominent modalities like olfaction, such as the smell of petrol or the smell of the inside of the car, and tactile information like a rush of air as a car drives past. Since speed in the real world is experienced in multiple modalities, mental simulations of speed should also involve multiple modalities. Previous work addressing mental simulation tends to focus on a single modality within one experiment (e.g. Meteyard et al., 2008) and the literature appears to focus heavily on the visual modality. One study tested the multimodality of simulations in sentences using a sentence-picture matching task and a sentence-sound matching task and found that simulations of spatial distance could be both visual and auditory (Winter & Bergen, 2012). For example, participants were faster to respond to a picture of a small milk bottle than a large milk bottle after reading the sentence "*You are looking at the milk bottle across the supermarket"* and faster to respond to a loud noise than a quiet noise after reading the sentence "*Right next to you someone fires a handgun*". However, the sentences only highlighted a visual or auditory feature, rather than using a single sentence to address the role of both modalities. Thus a further aim of the work in this chapter is to explore how single words produce activations in multiple modalities. This question tests whether mental simulations reflect real-world experience to the same level of detail. Here no particular modality of word meaning is highlighted because participants are presented with a single word with no sentence context.

I chose to investigate speed in the visual and auditory modalities because they are simple to produce in an experimental setting and intuitively appear to be the most important modalities in real-world speed perception. There may be differences in how visual and auditory information contribute to the meaning of speed words based on the preponderance of each modality in real-world experience. For example, the meaning of a word like *tree* is likely to be highly dominated by the visual modality because it is typically the only way that we interact with trees (unless we climb them, cut them etc.). Perceptual dominance has been shown to be an important predictor of word processing (Connell & Lynott, 2012a). It is possible that the meaning of most words is dominated by visual information since we live in a visually rich environment (Connell & Lynott, 2014). This is reflected in language itself, which encodes more visual distinctions than auditory: an analysis of noun concepts found eight times as many visually dominant concepts as auditorily dominant concepts (Lynott & Connell, 2013). Looking to research in perception there are many examples of visual dominance over other modalities (Colavita, 1974). When two modalities are in conflict, visual information dominates (Gibson, 1933). Well-known effects of this include the ventriloquism effect (Howard & Templeton, 1966) in which speech sounds are attributed to a different spatial location that contains a moving puppet, and the McGurk effect (McGurk & Donald, 1976) where mouth shape of a speaker affects what sounds are heard. These effects are explained by greater spatial acuity for vision than audition. There are exceptions though, for example, although vision dominates for spatial discrimination audition has been shown to dominate for temporal estimates (Recanzone, 2003) due to its greater temporal acuity. Since speed includes both spatial and temporal information it is possible that vision and audition are recruited to a similar extent in its representation.

4.2 The role of perceptual and verbal modality

Another aim of the experiments in this chapter is to test whether the modality of perceptual stimulus and the modality of the linguistic stimulus affect the nature of mental simulations. Connell & Lynott (2014) found that for words presented visually in a lexical decision task and reading-aloud task, processing of words with strong visual associations (e.g. *cloudy*) was facilitated, because visual attention was engaged. Words with strong auditory associations (e.g. *noisy*) were facilitated only for the reading-aloud task, which engaged auditory attention (in addition to visual attention). The type of perceptual attention engaged by the task interacted with perceptual information in the meaning of a word, affecting how efficiently the word was processed. In the present case, via a similar process of perceptual preactivation (Connel & Lynott, 2014), the type of attention directed to the perceptual speed stimulus and the speed words might affect the mental simulation of speed. Directing attention to the visual modality through a visual speed stimulus may facilitate the processing of visual words. This match in modality would lead to greater overlap of activation from the perceptual stimulus and the speed word than when the modalities mismatch, possibly leading to greater interaction between the two stimuli. It could be predicted then that an interaction between perceptual speed and word speed will be observed only when the two modalities match, but not when they mismatch. Or alternatively, the direction of interaction will differ between matching and mismatching modality, as in Kaschak et al. (2005) (see section 2.2.4 for a discussion about direction of effects).

To summarize, the following experiments investigate the simulation of speed in single speed verbs. By combining perceptual speed with speed words in a lexical decision task one can assess whether comprehension of speed verbs shares resources with real-world speed perception. This paradigm will reveal any behavioural consequences of interactions at the neural level. Both the modality of the perceptual stimuli and the modality of the word stimuli are manipulated in order to test firstly whether and to what extent speed simulations are multimodal and secondly, whether the modality of word presentation interacts with the modality of the perceptual stimulus. An embodied account of the comprehension of speed in language predicts an interaction between speed of perceptual stimulus and word speed such that response time will be different when the speeds match compared to when they do not match. Research suggests this interaction may differ depending on the match in modality between perceptual and verbal stimuli (Connell & Lynott, 2014). Finally, if perceptual modalities differentially contribute to real-world perception of speed, differences in the nature of the interaction when using perceptual stimuli of different modalities (visual or auditory) could be expected.

4.3 Experiment 4-1: No perceptual stimuli

Before testing the interaction of perceptual speed with speed words, I ran a simple lexical decision task, presenting speed verbs alone. This was to ascertain whether there were any inherent differences in processing fast and slow verbs, establishing a baseline for the further experiments. If to understand the meaning of speed verbs involves mental simulation, then response time to slow verbs may be slower than response time to fast words, because slow action takes longer to unfold. No differences in accuracy would be expected.

4.3.1 Method

4.3.1.1 Participants

30[1] participants (17 female)[2] were recruited from the UCL psychology subject pool to take part in the experiment. 4 participants were removed for having low overall accuracy (<80%).

4.3.1.2 Material

4.3.1.2.1 Norming

70 verbs of motion were chosen to be included in the norming study based on experimenter intuition and using an online dictionary and thesaurus. 20 participants conducted the norming task after completing an unrelated norming task for another experimenter, in a testing booth (demographics for these participants were misplaced, however the participants were taken from the UCL participant pool, of which the majority are university students). The norming task was located online in the form of a Google survey. Two versions of the survey were created with a different random order of items. Participants viewed verbs in past tense form, (because I also intended to use them in the sentences of the experiments in Chapter 8) and were instructed to rate their speed with the following instructions:

[1] Across experiments in this chapter, we decided upon the number of participants based on the lexical decision task conducted by Meteyard, Zokaei, Bahrami and Vigliocco (2008). However, since the data was sometimes collected as part of a lab class, this number was occasionally higher.

[2] Due to researcher error, information about participants' age was lost. However all subjects in this chapter were taken from the UCL subject pool or were UCL students so are of a similar demographic.

“*Please judge how fast you think the actions implied by the verbs below are. Please imagine that all verbs are in the form "the X verb to the Y" e.g. "The man moved to the car". Please rate a verb as "7" if you think it is very fast, and please rate a verb "1" if you think it is very slow. Use the values in between for other speeds. Please leave a question blank if you are unsure of the meaning of the verb.”*

Participants viewed a horizontal 7-point scale with “Very slow” written on the left side and “Very fast” written on the right side. Responses were made using the mouse by clicking a circle beneath a rating.

Verbs were classified as “fast” if both the mean and mode rating was greater than or equal to 5, and verbs were labelled as “slow” if both the mean and mode rating was less than or equal to 3. All remaining verbs were classified as “neutral”. This led to 23 verbs being classified as “slow”, 22 classified as “fast” and 25 classified as “neutral”. From this classification, 16 fast and 16 slow verbs were chosen (see Table Appendix 1-1 and 1-2). Verbs that suggested movement in a direction other than horizontal (e.g. *plunged*), verbs that denoted motion specific to a type of animal (e.g. *flew*) or verbs that denoted motion in water (e.g. *drifted*) were removed from selection. The two sets of fast and slow verbs could not be matched and significantly differed in log frequency HAL (taken from the English Lexicon Project) (t (30) = 3.1, p < .01) and in number of letters (t (30) = 3.33, p < .01) (means displayed in table 4-1). I therefore decided to regress out such variables within the analyses using linear mixed effects models (LME).

Table 4-1. Mean log frequency HAL and length for fast and slow verbs

Verb Type	Mean Log Frequency	Mean Length
Slow	3.36 (*SD* = 2.88)	6.06 (*SD* = 1.34)
Fast	6.39 (*SD* = 2.64)	7.44 (*SD* = .97)

An additional 32 words were used as filler words that were neutral words with no suggestion of motion (e.g. *desk*). 64 nonwords were formed using ARC Nonword

Database (Rastle, Harrington & Coltheart, 2002). All nonwords were 3-7 letters in length, orthographically legal and pronounceable

4.3.1.3 Procedure

The experiment was presented in E-prime. Visual presentation of the item appeared in the centre of the screen. The item remained on screen until a participant made a response. Participants were instructed to press 'j' on the keyboard if they saw a real English word and 'f' if they saw a nonword. The experiment contained two blocks with each word presented once in each block. Participants could choose to to take a break between blocks. Within each block word presentation was randomized. The whole experiment took around 20 minutes to complete.

4.3.2 Results

Individual trials were removed if response time was less than 250ms, greater than 3000ms or outside 2.5 *SD* of the participant's mean response time (3% of the data). For response time analysis, only correct trials were used.

Since the experimental items were not matched on relevant psycholinguistic variables response time and accuracy were analyzed using an LME with subjects and items as crossed random effects, partialling out word frequency (log frequency HAL), word length and neighbourhood size of each word, taken from the English Lexicon Project (http://elexicon.wustl.edu/) [3] . Markov chain Monte Carlo approximation was used in all analyses to estimate p values. No main effect of word speed was found for response time (β = .01, *t* =. 20, *p* =. 84) or accuracy (β = .02, *z* = .06, *p* = .95). Without controlling for these variables statistically there would be a significant difference in both response time (*t* (25) = 3.61, *p* <. 001) and accuracy (*t* (25) = 4.94, *p* <. 001). Average response time and accuracy are displayed in Figure 4-1.

[3] All following analyses of responses to visual words in this chapter are analysed using the same LME. Analyses with auditory words do not include number of orthographic neighbours as a covariate and include spoken duration (in ms) instead of word length.

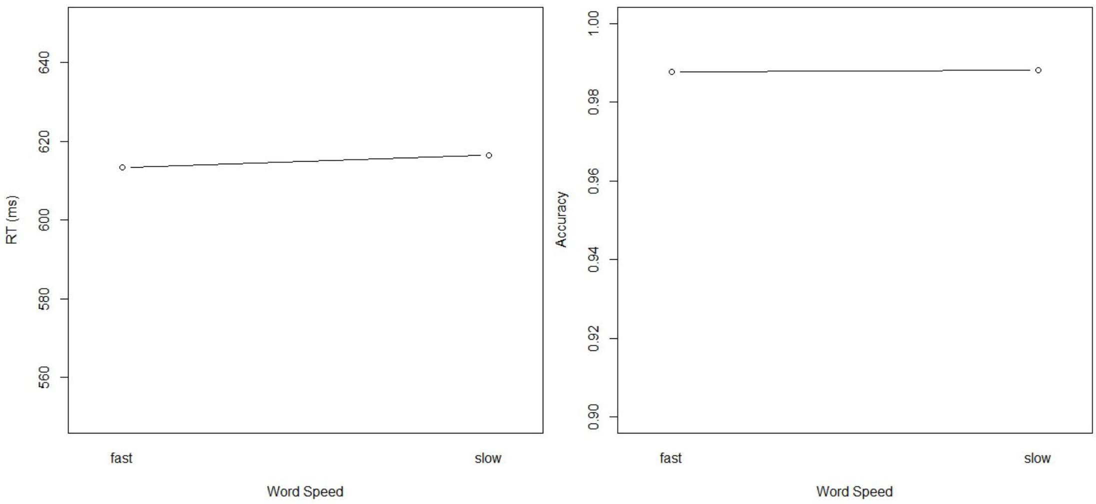


Figure 4-1. Model predicted response time and accuracy in Experiment 4-1 (visual words), after controlling for word length, word frequency and number of orthographic neighbours. Error bars reflect 1 standard error.

4.3.3 Discussion

Results showed no difference between response time to fast and slow words. From a simulation perspective slower responses to slow verbs than fast verbs could have been predicted if simulations reflect real-world events, because slow motion takes longer to unfold than fast motion. It is possible however, that differences in the duration of a simulation would not be evident for single words since they contain little information without context. Differences may be observed if verbs were placed in a sentence including specific agents. Further, the simulation of speed in single words may only be detectable by combining speed in perception with the speed words, as in the experiments below. Experiment 4-1 has set a baseline for the following experiments such that any differences observed between fast and slow verbs must be due to the interaction with perceptual speed.

4.4 Experiment 4-2: Visual speed (horizontal) and visual words

In Experiment 4-2 participants were presented with a fast or slow visual stimulus before being presented with a visual word. The visual stimulus was a horizontal line moving rightwards across the centre of the screen at either a fast or slow speed. The line began at the left edge of the screen and increased in length until the centre of the screen. This stimulus was intended to produce a horizontal portrayal of speeded motion most similar to the everyday experience of motion perception (i.e. we typically perceive moving objects, such as cars, as moving horizontally across our visual field).

4.4.1 Method

4.4.1.1 Participants

40 participants (28 female) took part in the experiment either as part of a laboratory demonstration class or were recruited from the UCL psychology subject pool and took part for payment (mean age = 21.73, *SD* = 4.5).

4.4.1.2 Material

Items were identical to those used in Experiment 4-1 and the perceptual stimulus was a horizontally moving black line drawn online during the experiment.

4.4.1.3 Procedure

The experiment program was created using Cogent in Matlab and presented on a standard CRT monitor. On each trial, a black line moved horizontally across the centre of the screen. The line began at the left side of the screen and increased in length, rightwards, to the centre of the screen. The line would move at either a fast or slow speed (hereby referred to as fast prime or slow prime). The slow prime was drawn at a rate of 8 pixels per screen refresh and the fast prime was drawn at a rate of 24 pixels per screen refresh. When the line reached halfway across the screen it stopped and a word was presented in the centre of the screen (see Figure 4-2). Participants had to decide whether the item was a real word or not and responded with the keyboard (‘j’ if it was a real English word, ‘f’ if it was a non-word). Each item appeared twice, once with each speed of line and presented in separate blocks. Within each block items were presented randomly. Both accuracy and response times were recorded.

4.4.2 Results

Five items were removed from analysis for having low overall accuracy (<80%: *traipse, plod, dally, trudge, saunter*). Individual trials were removed if response time was less than 250ms, greater than 3000ms or outside 2.5 *SD* of the participant's mean response time (2% of the data). For response time analysis, only correct trials were used.

Mean response time and accuracy for the four conditions are displayed in Figure 4-3. No effect of word type was found, no effect of prime and no interaction (*t*s < 1). There was a main effect of prime speed in accuracy (β = .24, z = 2.14, p = .03), no effect of word speed (β = -.02, z = .84, p = .4) and a marginally significant interaction between word speed and prime speed (β = .22, z = 1.88, p =. 06). The marginal interaction was followed up with simple effects LMEs, finding a significant effect of prime speed for fast words (β = .41, z = 2.07, p = .04) but not for slow words (β = .05, z = .31, p = .76). Responses for fast words were less accurate with fast lines than with slow lines.

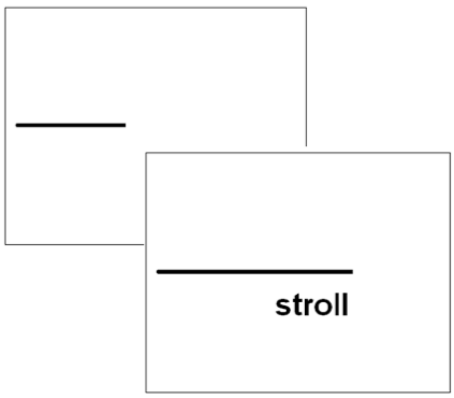


Figure 4-2. Example of display used in Experiment 4-2.

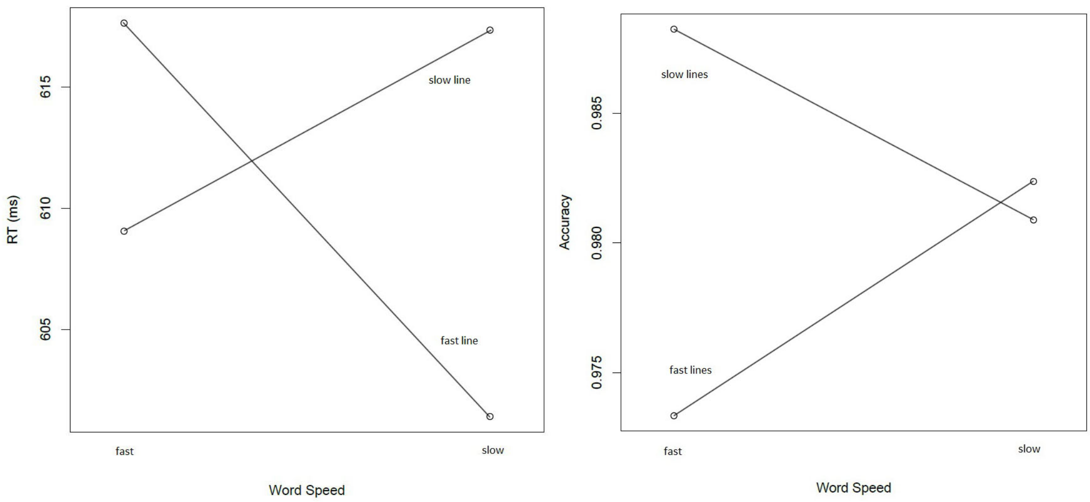


Figure 4-3. LME predicted means for response time and accuracy in Experiment 4-2 (visual speed (horizontal) and visual words).

4.4.3 Discussion

Using a horizontal moving speed prime I did not find the predicted interaction between prime speed and verb speed in response time. I did however find a marginal interaction in accuracy suggesting that participants make more mistakes when both the word and prime are fast. Although I did not predict an effect in accuracy, this result would support embodied theories: activations caused by the fast moving stimulus interfered with processing of the fast words, which led to mistakes. But, note that the interaction did not meet conventional levels of statistical significance ($p > 0.05$). One reason for the lack of an effect in response time could be that participants' attention was too focused on the centre of the screen in anticipation of the upcoming item that they did not sufficiently process the visual speed stimulus. To test this explanation I decided to introduce a perceptual speed manipulation in the auditory domain. If speed sounds were played through headphones while participants completed a visual lexical decision task, the sounds would be difficult to ignore.

4.5 Experiment 4-3: Auditory speed (beeps) and visual words

Experiment 4-3 investigated the effect of a speeded auditory stimulus on speed verb comprehension. Fast and slow auditory stimuli were presented to participants through headphones before they viewed the visual item on screen. The stimulus in this experiment was intended to be an auditory resemblance of the visual speed stimulus in Experiment 4-2 with sounds moving horizontally at a fast or slow speed. If simulations of speed include auditory information, I would expect to find an interaction between word speed and auditory speed. Although I did not find an effect in response time in Experiment 4-2, the use of an auditory stimulus may be more successful because auditory attention is not taxed by the task.

4.5.1 Method

4.5.1.1 Participants

30 participants (16 female) were recruited from the UCL psychology subject pool and took part in the experiment for payment (mean age = 27.48, *SD* = 11.5).

4.5.1.2 Material

Auditory speed stimuli were created using the auditory software Audacity. Beeps were presented as moving from left ear to right ear (i.e. horizontally) by using the pan feature, which manipulates the percentage of sound played to each ear. In addition the time between each beep was manipulated to be shorter or longer to create a fast or slow stimulus respectively. There was a pause of 50ms between each beep in the fast condition and a pause of 1000ms in the slow condition. Full stimulus duration was 3000ms. Based on these parameters, the slow stimulus appeared to move only halfway between the left and right ear, whilst the fast stimulus moved from the left ear to the right ear and back to the left ear. Using a horizontal moving stimulus a trade-off between distance and time had to be made. I chose to match each stimulus on duration to be coherent across experiments.

4.5.1.3 Procedure

The experiment was presented in E-prime. On each trial a fixation-cross appeared in the centre of the screen followed by the auditory stimuli presented through headphones. After 3 seconds the sound stopped and the item appeared in the centre of the screen. All other experimental details are identical to Experiment 4-2.

4.5.2 Results

Six items were removed from analysis for having low overall accuracy (<80%: *traipse, plod, dally, dawdle, trudge, saunter*). Individual trials were removed if response time was less than 250ms, greater than 3000ms or outside 2.5 *SD* of the participant's mean response time (4% of the data). For response time analysis, only correct trials were used.

Average response time and accuracy are displayed in Figure 4-4. Results showed a significant main effect of auditory speed (β = -.07, t = 3.18, p <. 001) with response times faster following slow beeps than fast beeps. There was no effect of verb speed (β = -.02, t = .749, p =. 45) and no interaction between beep speed and verb speed (β = .01, t = .552, p = .58).

For accuracy, there was no effect of beep speed (β = -.13, z = .49, p = .62), no effect of word speed (β = -.09,z = .28, p= .78) and no interaction between the two (β = .01, z = .07, p = .94).

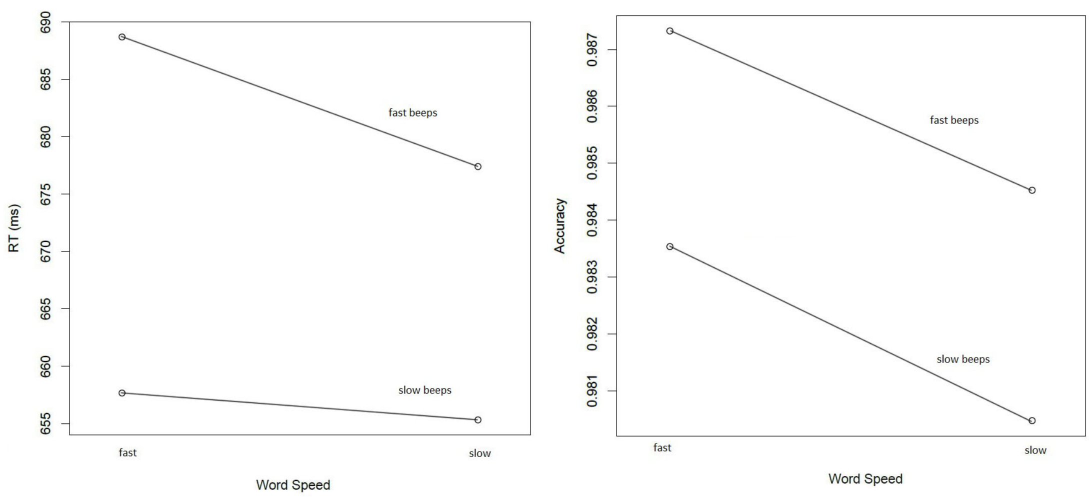


Figure 4-4. LME predicted response time and accuracy in Experiment 4-3 (auditory speed (beeps) and visual words).

4.5.3 Discussion

Experiment 4-3 found a main effect of auditory speed only, in which responses were faster following slow beeps than fast beeps. It is likely that the pattern of slow beeps was more predictable that fast beeps and hence responses were facilitated. The fact that no interaction was observed suggests either that auditory speed is not recruited as part of the comprehension of speed verbs, or alternatively that the auditory stimulus did not create fast and slow auditory speed to sufficiently affect processing of the speed words.

Both Experiment 4-2 and 4-3 failed to find an interaction between perceptual speed and word speed. Before concluding that visual and auditory information is not crucial to the comprehension of speed words, some methodological aspects need to be addressed. There are details about the perceptual stimuli that could be improved. For Experiment 4-2, the moving line stopped in the same position at the same time for each prime and the word subsequently appeared making the stimulus and word presentation very predictable. Thus, by focusing on the centre of the screen, the moving line could be ignored. It is possible then that the motion stimulus was not sufficiently processed and participants simply fixated the centre of the screen in anticipation of the upcoming word. For Experiment 4-3, the gaps between the beeps were unnatural: auditory speed in the real world is often a continuous sound (e.g. imagine the sound of a car speeding along a motorway). Additionally, the motion created by both the visual and auditory stimulus (i.e. of someone/something independent of an observer moving horizontally) may not have implied the same *type* of movement as that implied by the verbs: a sense of personal movement or self-relevance may have been necessary. Experiments 4-4 & 4-5 therefore used a visual and auditory stimulus that created a sense of motion, similar to vection, inducing motion more relevant to the self.

4.6 Experiment 4-4: Visual speed (vection) and visual words

Experiment 4-4 attempted to create a more self-relevant visual speed stimulus. On each trial two lines moved out from the centre of the screen continually at either a fast or slow speed (fast vs. slow prime). This display induced the feeling of moving forwards either quickly or slowly.

4.6.1 Method

4.6.1.1 Participants

32 participants (18 female) were recruited from the UCL psychology subject pool and took part in the experiment for payment (mean age = 25.84, *SD* = 6.43). Seven participants were removed from analysis for having slow overall response time to correct experimental trials (> 1200 ms).

4.6.1.2 Procedure

The experiment was run in Matlab. Participants were seated in a central position in front of the monitor. Each trial began with two lines moving outwards from the centre of the screen in a grid-like display (see Figure 4-5). Lines moved quickly or slowly: slow lines had two cycles and fast lines had six cycles. [4]After 3 seconds the line movement stopped and the item appeared in the centre of the screen, within the static grid. All other experimental details are identical to Experiment 4-2.

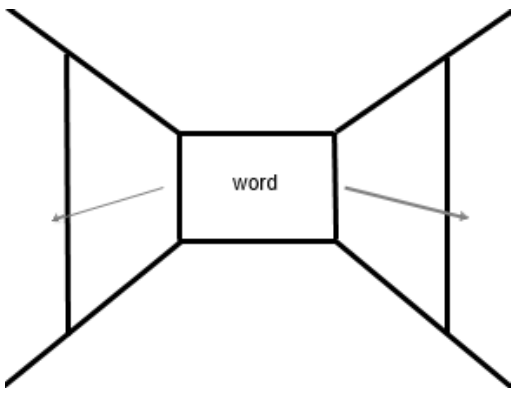


Figure 4-5. Example of display used in Experiment 4-4 and 4-6.

[4] The visual stimulus was designed by second year mini-project student Joanna Evershed

4.6.2 Results

Two items were removed from analysis for having low overall accuracy (< 80%: *dally* and *traipse*). Individual trials were removed if response time was less than 250ms, greater than 3000ms or outside 2.5 *SD* of the participant's mean response time (8% of the data). For response time analysis, only correct trials were used.

Average response time and accuracy are displayed in Figure 4-6. A significant effect of prime was found (β = .002, t = 1.96, p = .05) in response time with slow moving lines leading to slower mean response times than fast moving lines. There was no effect of word type (β = -.01, t = 1.25, p = .2) but there was a significant interaction between word type and prime speed (β = .06, t = 2.87, p < .001). Planned comparisons revealed that for fast words response time was faster with fast lines than with slow lines (β = .06, t = 2.05, p = .04), and for slow words responses were faster with slow lines than fast lines (β = .07, t = 2.03, p = .04). There was no effect of word type (β = .17, z = 1.07, p =. 29), no effect of prime speed (β = .38, z = .9, p = .37) and no interaction (β = -.11, z =. 66, p = .5) in accuracy scores.

4.6.3 Discussion

Using a visual speed stimulus that portrayed movement in perspective as though an observer was moving forwards, an interaction between visual speed and word speed was found in response time. Responses were significantly faster when the speed of the visual stimulus matched the speed of the verb. This suggests that comprehending speed verbs shares processes with the visual perception of speed. When these areas were preactivated by the visual stimulus they facilitated processing of subsequent words with the same speed. The following experiment investigates whether a similar effect can be observed for auditory speed.

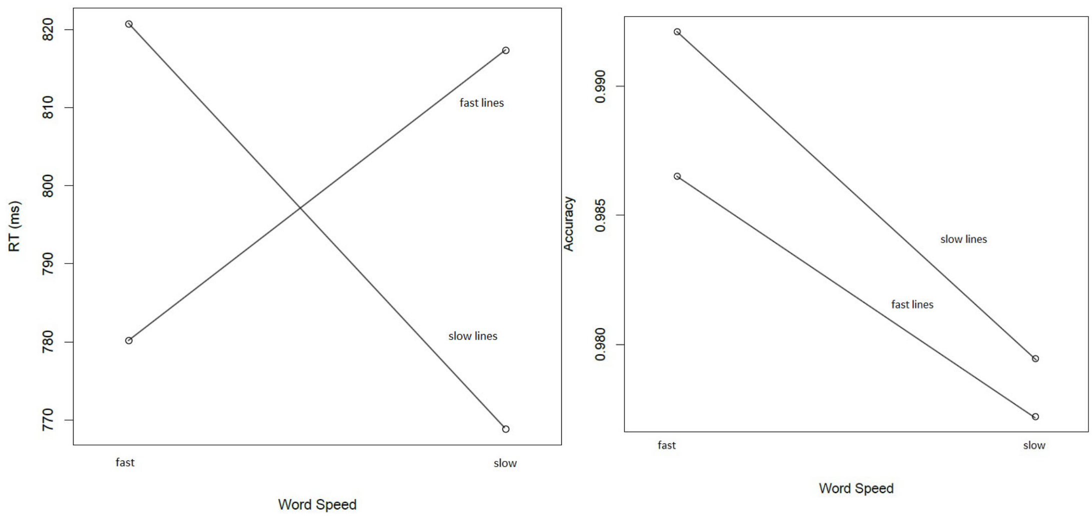


Figure 4-6. LME predicted means for response time and accuracy in Experiment 4-4 (visual speed (vection) and visual words).

4.7 Experiment 4-5: Auditory speed (white noise) and visual words

Mirroring Experiment 4-4, Experiment 4-5 used an auditory stimulus that presented motion more relevant to the observer: motion moving towards rather than horizontally.

4.7.1 Method

4.7.1.1 Participants

67 participants (56 female) took part in the experiment as part of a first year psychology lab class (mean age = 18.6, *SD* = 0.86). Two participants were removed from analysis for having slow average response time to correct experimental trials (>2SD from group mean).

4.7.1.2 Material

An auditory stimulus was taken from Kaschak et al.'s (2005) "towards" condition. This was white noise producing the sound of motion towards the listener. The sound file was edited in Audacity using the 'Change Tempo' effect to create a fast and slow version of the sound. This option changes the speed of the sound without changing pitch.

4.7.1.3 Procedure

Participants listened to fast or slow moving white noise for 3 seconds through headphones before being presented with the stimulus in the centre of the screen. All other experimental details were identical to Experiment 4-2.

4.7.2 Results

Seven items were removed from analysis for having low overall accuracy (<80%: *amble*, *dally*, *dawdle*, *plod*, *saunter*, *traipse*, *trudge*). Individual trials were removed if response time was less than 250ms, greater than 3000ms or outside 2.5 *SD* of the participant's mean response time (3% of the data). For response time analysis, only correct trials were used.

Mean response time and accuracy are displayed in Figure 4-7. A significant effect of auditory speed was found in response time (β = .06, t = 2.78, p < .01) with faster response times following slow sounds than fast sounds. There was no effect of word speed (β = .02, t = 1.3, p = .19) and no interaction between word speed and prime speed (β = .01, t = .81, p = .42). No effect of word speed (β = -.1, z = .33, p = .75), no effect of auditory speed (β = .07, z = 1.3, p = .19) and no significant interaction (β = .16, z = 1.62, p = .1) were found in accuracy.

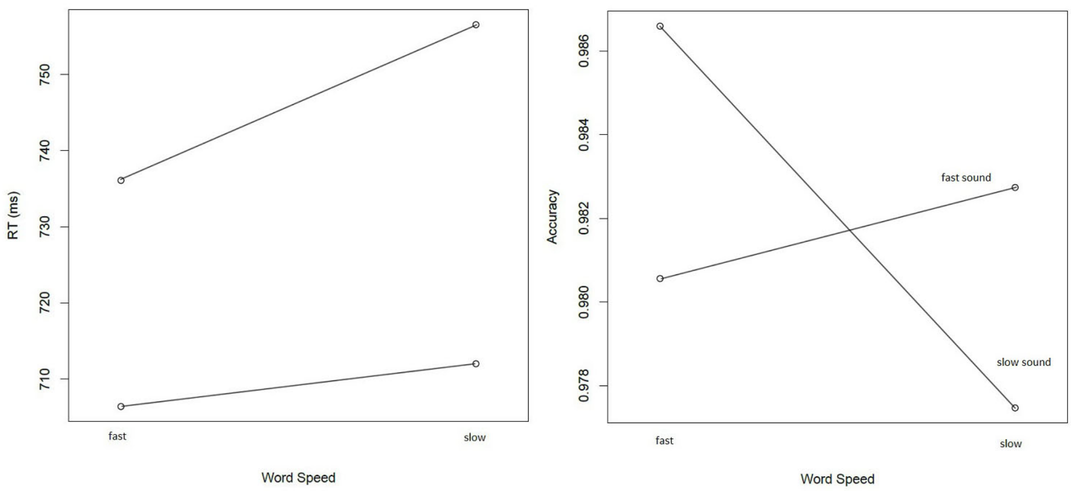


Figure 4-7. LME predicted means for response time Experiment 4-5 (auditory speed (white noise) and visual words).

4.7.3 Discussion

Experiment 4-5 found a significant effect of auditory speed with slow sounds leading to faster reaction times than fast sounds. As with Experiment 4-3, this may have been because the end of the slow sound was more predictable than the fast sound. No interaction between auditory speed and word speed was found, which suggests that the white noise did not create a sense of motion comparable to the visual stimulus used in Experiment 4-4, or that auditory motion is not simulated in speed verb comprehension. Alternatively, an effect of auditory speed may not have been observed because the words were presented visually and not auditorily. This mismatch in modality may have reduced the overlap between perceptual speed and word speed. The following experiment begins to address the question of match in modality between perceptual stimulus and word.

4.8 Experiment 4-6: Visual speed (vection) and auditory words

An interaction was found when speed was manipulated visually (Experiment 4-4) but not when speed was manipulated auditorily (Experiment 4-5). In both studies the speed words were presented visually which meant that modalities of perceptual stimuli and verbal stimuli matched in Experiment 4-4 but not in Experiment 4-5. The interaction between perceptual speed and word speed may be a unimodal effect and not crossmodal, meaning that perceptual stimuli can only affect words presented in the same modality. Hence the null result in Experiment 4-5 may have been due to modality mismatch. I sought to test this hypothesis by rerunning both experiments using auditory presentation of speed words. If simulations are unimodal then I would predict an interaction between perceptual speed and word speed with the auditory speed stimulus but not the visual speed stimulus.

4.8.1 Method

4.8.1.1 Participants

30 participants (average age 25.17 (*SD* = 11.18)) of which 18 were female were recruited from the UCL psychology subject pool and paid for their participation. Three subjects were removed due to low overall accuracy (< 80%).

4.8.1.2 Material

The same visual stimulus from Experiment 4-4 was used. The same set of items was used but an auditory version was recorded in Audacity by a native English speaker.

4.8.1.3 Procedure

As in previous experiments, the visual stimulus was presented for three seconds and then the word was played through headphones. Participants could respond at any point after word onset. All other details were identical to Experiment 4-2.

4.8.2 Results

Four items were removed for overall low accuracy (<80%: *bolt*, *crawl*, *dawdle*, *hurry*). Individual trials were removed if response time was less than 250ms, greater than 3000ms or outside 2.5 *SD* of the participant's mean response time (3% of the data). For response time analysis, only correct trials were used.

Mean response time and accuracy are displayed in Figure 4-8. There was no effect of word speed (β = .04, t = .78, p = .44), no effect of visual speed (β = .01, t = .35, p =

.72) and no interaction between word type and prime speed (β = .01, t = .49, p = .63) in response time. For accuracy, a significant effect of visual speed was found (β = .30, z = 2.02, p = .04) such that responses were less accurate following fast lines compared to slow lines, but there was no effect of word speed (β = .55, z = 0.82, p = .42) and no significant interaction (β = -.22, z = 1.55, p = .12). Thus the interaction observed in Experiment 4-4 was not replicated suggesting that match in modality is an important factor.

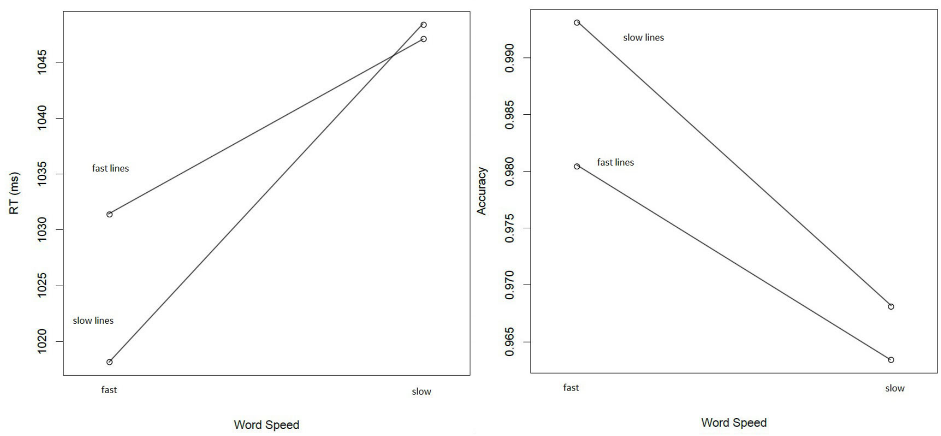


Figure 4-8. LME predicted means for response time and accuracy Experiment 4-6 (visual speed (vection) and auditory words).

4.9 Experiment 4-7: Auditory speed (white noise) and auditory words

This experiment replicated Experiment 4-5 but used auditory instead of visual words in order to test whether a match in modality of perceptual and verbal stimuli is important.

4.9.1 Method

4.9.1.1 Participants

45 participants (21 female) were recruited from the UCL psychology subject pool (average age 25.87 (SD = 10.15)) and paid for their participation. Five subjects were removed due to low overall accuracy (< 80%).

4.9.1.2 Procedure

The experimental procedure was identical to Experiment 4-5, presenting fast and slow white noise through headphones for three seconds, except that experimental items were presented auditorily through headphones. Each item was presented at the offset of the speed stimuli.

4.9.2 Results

Five items were removed for overall low accuracy (< 80%: *bolt*, *dally*, *dawdle*, *hurry*, *saunter*). Individual trials were removed if response time was less than 250ms, greater than 3000ms or outside 2.5 *SD* of the participant's mean response time (11% of the data). For response time analysis, only correct trials were used.

Mean response time and accuracy are displayed in Figure 4-9. There was no effect of word type (β = .10, t = 1.66, p = .1), no effect of auditory speed (β = -.03, t = .55, p = .58) and no interaction between word type and prime speed (β = .01, t = .78, p = .44) in response time. For accuracy no effect or word type was found (β = .04, z = .078, p = .94), no effect of visual speed (β = .03, z = .18, p = .86) and no significant interaction (β = .05, z = .62, p = .54).

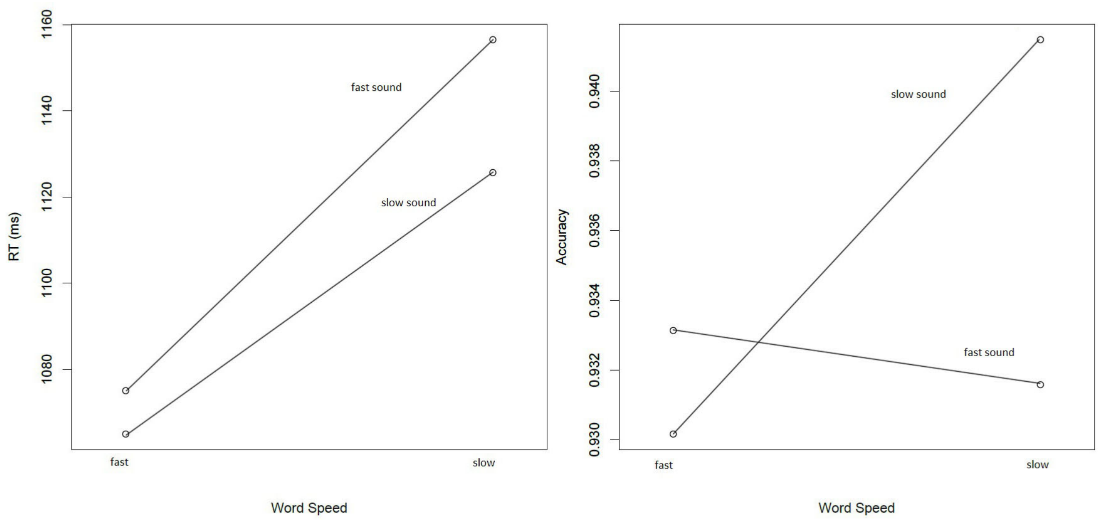


Figure 4-9. LME predicted response time and accuracy in Experiment 5-7 (auditory speed (white noise) and auditory words).

4.9.3 Discussion Experiment 4-6 and 4-7

Experiment 4-6 failed to replicate the interaction found in Experiment 4-4 with the same visual stimulus, and again in Experiment 4-7, the auditory stimulus failed to produce an interaction. The lack of effect in Experiment 4-6 (visual vection and auditory words) may be due to the mismatch in modality of perceptual stimuli and verbal stimuli, as discussed earlier. Or alternatively, since the task required participants to use auditory attention to respond to the words, it is possible that they did not process the moving visual stimulus at all but simply listened to the words and looked towards the keyboard in order to respond. This explanation cannot be applied to Experiment 4-7 (auditory white noise and auditory words) because both the perceptual stimulus and the words were presented in the same modality, so the participants must have processed the stimulus. One problem with the auditory stimulus is that white noise is an abstract sound and cannot be applied to a particular object or movement. In fact, unless you were told that it is a motion sound it may have been unidentifiable. In Experiment 4-7, some participants were asked how they would describe the sounds and few used the word “motion”. One person described it as sounding like the sea. It is therefore possible that the auditory “motion” stimulus is insufficient to create motion similar to that implied by the verbs. As a final step in this investigation, I decided to use an auditory stimulus that clearly implied human speeded motion: fast and slow footsteps.

4.10 Experiment 4-8: Auditory speed (footsteps) and auditory words

Footstep sounds have been shown to successfully imply speed in other studies (Brunye, Mahoney & Taylor, 2010). Brunye et al. (2010) found that fast footsteps sped up reading time compared to slow footsteps for route descriptions (ground-level perspective) but not survey descriptions (aerial overview perspective). Further, fast footsteps led participants to estimate larger distances between described landmarks compared to slow footsteps. This is thought to be because readers’ estimates of distance were based on how quickly they simulated motion through an environment, which was affected by speed information present in the footsteps. This effect was not found for metronome pulses.

If footsteps sounds do successfully imply fast and slow motion then I expect a similar interaction to be observed as that of Experiment 4-4 (visual vection and visual words): faster reaction times when speed of footsteps matches speed of verbs compared to when speed of footsteps do not match speed of verbs.

4.10.1 Method

4.10.1.1 Participants

52 subjects (average age = 23.33, *SD*=6.79, 34 females) were recruited from the UCL psychology subject pool and paid for their participation. Four were removed for having average accuracy less than 80%, and one was removed for slow average response time (>1400ms (longer cutoff due to words being presented auditorily)).

4.10.1.2 Material

The sounds of fast and slow footsteps were taken from an online sound database (www.freesound.org). The sounds of footsteps implied either walking or running on gravel. The slow stimulus contained five footsteps and the fast stimulus contained 10 footsteps, within three seconds.

4.10.1.3 Procedure

Participants listened to fast or slow footsteps for three seconds before items were presented auditorily.

4.10.1.4 Procedure

The procedure was identical to previous experiments except that during the instruction phase participants were told that they would hear the "sound of footsteps". Participants were informed to reduce ambiguity in identification of the sound (although they clearly reflected a human walking or running). Giving the participants this information did not compromise the study or alert participants to the study aims since speed was not mentioned and they were not informed of any link between the sound and the task.

4.10.2 Results

Three items were removed from analysis for having low overall accuracy (< 80% *dawdle*, *dally* and *traipse*). Individual trials were removed if response time was less than 250ms, greater than 3000ms or outside 2.5 *SD* of the participant's mean response time (4% of the data). For response time analysis, only correct trials were used.

Mean response time and accuracy are displayed in Figure 4-10. For response time there was no main effect of footstep speed ($\beta = .01$, $t = 1.16$, $p = .25$) and no effect of word speed ($\beta = .03$, $t < 1$). There was however a significant interaction between word speed and prime speed ($\beta = .03$, $t = 2.12$, $p = .03$). Planned comparisons revealed that there was a marginal effect of footstep speed for slow words ($\beta = .04$, $t = 1.98$, $p = .06$), with responses slower with slow footsteps than fast footsteps, but no effect of footsteps for fast words ($\beta = -.02$, $t = 1.14$, $p = .28$), although there was a trend in the opposite direction to that for slow words. A significant effect of word speed on accuracy was found ($\beta = .53$, $z = 4$, $p <. 001$), with accuracy lower for slow words than fast words, but no effect of footsteps speed was found ($\beta = .14$, $z =1.26$, $p = 0.21$) and no interaction ($\beta = .003$, $z = .64$, $p = .52$).

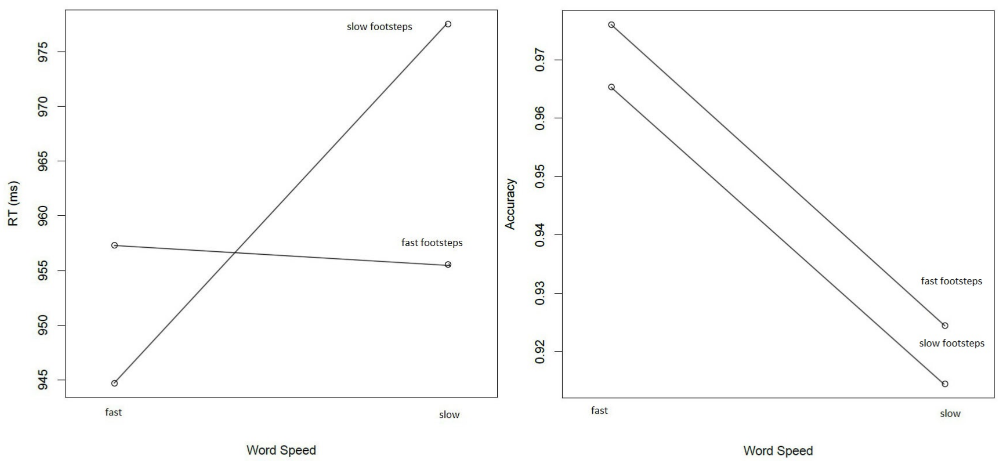


Figure 4-10. LME predicted response time and accuracy Experiment 4-8 (auditory speed (footsteps) and auditory words).

4.11 Experiment 4-9: Auditory speed (footsteps) and visual words

This experiment replicated Experiment 4-8 except that words were presented visually instead of auditorily in order to test whether the interaction between perceptual speed and word speed was dependent on match in modality.

4.11.1 Method

4.11.1.1 Participants

44 subjects (average age 21.95, *SD* = 4.1, 32 female) were recruited from the UCL psychology subject pool and paid for participation). One subject was removed for slow average reaction time (>3*SD* overall mean of subjects).

4.11.1.2 Material and Procedure

The material and procedure were identical to Experiment 4-8 except that words were presented visually at the offset of the auditory stimuli.

4.11.2 Results

Four items were removed from analysis due to low accuracy (< 80%: *dawdle*, *plod*, *trudge* and *traipse*).

Mean response time and accuracy are displayed in Figure 4-11. There was no main effect of footstep speed (β = .03, t = 1.4, p = .16), no effect of word speed (β = .03, t = .62, p = .54) and no interaction between word speed and prime speed (β = .003, t = .2, p = .84) in response time. For accuracy no effect of word speed was found, no effect of footsteps speed and no interaction (zs < 1).

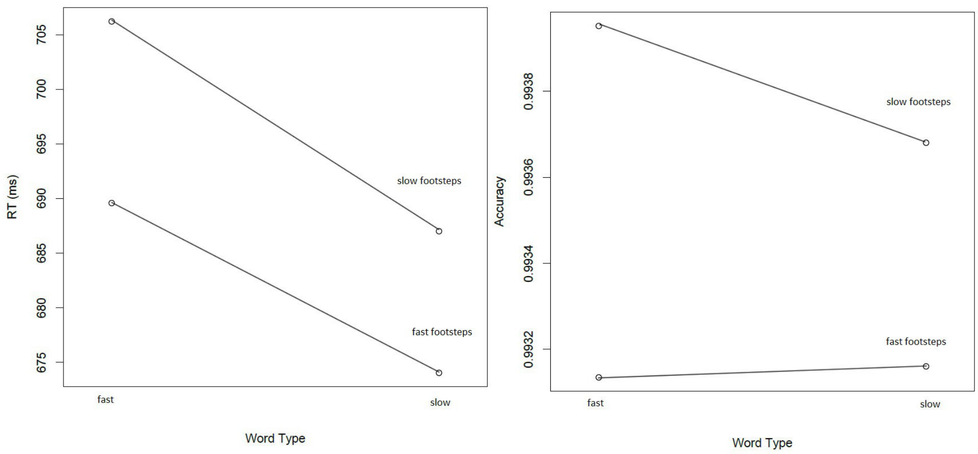


Figure 4-11. LME predicted response time and accuracy Experiment 4-9 (auditory speed (footsteps) and visual words). Discussion Experiments 4-8 and 4-9

The sound of footsteps produced a significant interaction between perceptual speed and word speed when words were presented auditorily (i.e. there was a match in modality). Responses were slower when the speed of footsteps matched the speed of verb. This pattern is opposite to that observed in Experiment 4-4 (visual vection and visual words) where responses were faster when the speed of moving lines matched the speed of verbs. Experiment 4-8 provides evidence for auditory simulation during comprehension of speed verbs. Finding a significant interaction using footstep sounds suggests that the simulations used to understand speed words are not general, abstract simulations of speed, but are specific to simulations of the body in motion because an abstract auditory motion stimulus did not interact with word speed (Experiments 4-3, 4-5 & 4-7). The sound of footsteps implied an agent in motion, which matched the types of movements described in the verbs. Further, the interaction was only observed when verbal and perceptual stimuli were presented in the same modality. These findings are discussed further in the General Discussion below.

4.12 General Discussion

In this chapter I used a lexical decision paradigm combining speed verbs with visual or auditory perceptual stimuli that portrayed fast and slow motion. Results from reaction times showed that verb speed and perceptual speed interacted when the perceptual stimulus was either visual lines moving outwards in perspective or the sound of footsteps (results summarized in Table 4-2). These stimuli specifically emphasized motion of the body in comparison to the other perceptual stimuli used that evoked more abstract motion depictions. The interaction was only observed when the modality of the perceptual stimuli and word stimuli matched (i.e. visual vection and visual words, auditory footsteps and auditory words). Moreover, the nature of the interaction differed between auditory and visual modalities. When the perceptual and word stimuli were visual (Experiment 4-4) a facilitation effect was observed, with response times faster when the speed of perceptual stimuli matched the speed of verb. Conversely, when the perceptual and word stimuli were auditory (Experiment 4-8), an interference effect was observed: response time was slower when speed of perceptual stimuli matched speed of verb. It is important to note that when the speed verbs were presented without a preceding perceptual stimulus (Experiment 4-1) there was no difference in response time between fast and slow verbs and so any differences observed in the following experiments must be due to interactions with the speeded perceptual stimuli. Below I address each of the three interesting findings to emerge from this chapter that describe when these effects were observed (relevance of body and modality match) and what the interactions looked like (difference between modality).

Table 4-2. Summary of experiments conducted in Chapter 4

Experiment	Perceptual modality	Perceptual stimulus	Verbal modality	Modality match	Result
1	n/a	n/a	visual	n/a	n/s
2	visual	horizontal lines	visual	match	n/s
3	auditory	horizontal beeps	visual	mismatch	n/s
4	visual	moving lines (vection)	visual	match	facilitation effect in RT
5	auditory	white noise towards participant	visual	mismatch	n/s
6	visual	moving lines (vection)	auditory	mismatch	n/s
7	auditory	white noise towards participant	visual	mismatch	n/s
8	auditory	footsteps	auditory	match	interference effect in RT
9	auditory	footsteps	visual	mismatch	n/s

4.12.1 When are speed simulations observed?

Results suggest that there are two factors that play a role in whether or not an interaction between perceptual speed and word speed will be observed. The first factor is whether or not the perceptual stimulus reflects real biological motion compared to abstract motion and the second factor is whether the modality of perceptual stimulus and the modality of the words match or not. Below I discuss these factors and some potential explanations for them.

4.12.1.1 The role of the body

The results suggest an important role of the body in speed simulations. Interactions between speed of perceptual stimuli and speed of words were not observed when the perceptual stimuli were abstract depictions of speed and did not imply an agent. Instead interactions were found when the perceptual stimuli involved the body: the visual stimulus in Experiments 4-4 was a display that created a sense of forward motion in the participant and the auditory stimulus in Experiments 4-8 was the sound of actual human movement. In comparison, the horizontal moving line (Experiment 4-2), moving beeps (Experiment 4-3) and white noise stimuli (Experiment 4-5 and 4-7) were very removed from human motion events. In fact, one participant described the white noise stimuli as sounding like “the sea”. Below I propose two potential explanations for this “body relevance” effect that are not necessarily mutually exclusive.

4.12.1.1.1 Simulations of speed are specific to biological motion

The first possible explanation is that simulations for speed verbs include representations of fast and slow motion specifically performed with the body, or specifically biological motion, and not a general speed simulation abstracted away from an agent. In this case, real perceptual speed will affect speed verb comprehension only when that perceptual speed is depicted via human motion because this matches the nature of the action described by the word. Although elsewhere effects of an abstract visual stimulus on lexical decisions has been found

(Meteyard et al., 2009), this was not for verbs that described actions specifically performed with the body but verbs that could also be applied to non-biological entities. For example, the words *rise* and *fall* could describe movement of a balloon and a rock, and these may be more dominant meanings than a man *rising* from his chair or a child *falling* from a swing. The items used in the present experiments strongly refer to actions performed with a human body, whereas the Meteyard et al. (2009) items are likely to involve motion representations abstracted away from specific entities, and thereby possibly involve motion simulations that are more abstract and schematic.

4.12.1.1.2 Simulations of speed involve action preparation

A second explanation for why interactions were only observed with body-relevant stimuli is that they may only occur when the perceptual stimuli forces the comprehender into a state of movement or movement preparation. The visual stimulus of Experiment 4-4 produced an illusion of real physical movement (vection) and the sound of footsteps could have primed full body movements either via auditory mirror neurons which discharge when listening to sounds produced by actions (Kohler, Keysers, Umiltà, Fogassi, Gallese & Rizzolatti, 2002) or because they signalled incoming threat (or both). This view implies that simulations have an egocentric perspective. Simulating the self in motion is in line with the proposal that people understand action verbs as describing actions they would perform with their own body rather that a general representation of how other people use their bodies (Casasanto, 2014). Rueschemeyer et al. (2010) found that a motion sensitive area of the brain (middle temporal (MT) area) was activated by sentences describing motion towards a participant but not sentences describing motion away from the participant, reflecting the importance of self-relevance in simulation. They also found activated regions along the cortical midline, part of a network involved in the guidance of visual attention and change of behaviour when under threat. Self-relevance may therefore lead to action preparation in response to incoming stimuli. Further, action sounds are crucial for signalling socially dangerous or unpleasant events (Aglioti & Pazzaglia, 2010) and the sound of footsteps may signal a threat. From an ecological perspective, prioritizing such sounds serves as an advantage to survival if approaching sounds signal a threat to safety. It is possible then that the footsteps have a biological and emotional significance that increases arousal. Note that the footsteps here were not approaching or receding but were at a constant distance from the perceiver, sounding more like the footsteps of the listener themselves than another person. Thus the listeners may have attributed the sound of footsteps to their own movements rather than the sounds increasing their level of alertness and arousal, either way leading to a state of action preparation.

These two hypotheses (speed simulations are specific to biological motion and speed simulations involve action preparation) may implicate different neural loci for speed simulation. The first hypothesis suggests that speed simulations occur in motion-specific regions, such as MT (see Gennari, 2012 for discussion), or regions specific to processing biological motion, for example posterior superior temporal sulcus (Grossman, Donelly, Price, Mogan, Pickens, Neighbor & Blake, 2000; Grossman, Battelli & Pascual-Leone, 2005). If comprehending speed in language involves action preparation then simulations are likely to occur in regions of the motor or premotor cortex that have been shown to be involved in action planning and execution (Hauk et al., 2004). It is possible that speed simulation occurs within both motion processing and motor regions depending on the context or situation described in the language (for example emphasizing action observation versus action participation).

If humans are sensitive to approaching sounds then it seems odd that the white noise stimuli failed to affect word comprehension since the sound moved towards the participant. But, there are clear separate neural systems for action-related sounds and non-action related sounds (Pizzamiglio, Aprile, Spitoni, Pitzalis, Bates, D’Amico & Di Russo, 2005) and action sounds are more important and perceptually prioritized in threat monitoring. Since white noise is a non-action-related sound it would not be perceived as relevant to the self.

4.12.1.1.3 Role of the body: conclusion

For an interaction between perceptual speed and word speed to be observed, the perceptual stimulus needs to be relevant to the body in some way. This could mean that speed simulations reflect biological motion specifically and not abstract motion, or that speed simulations occur in motor processing regions, possibly with an egocentric perspective. Based on the present experiments it is not clear which of the two explain the present data, or whether both play a role. It is also likely that the contribution of biological motion simulation and action simulation to speed word comprehension differs depending on task and context (e.g. a sentence context emphasizing whether speed refers to a separate agent or the comprehender).

4.12.1.2 Match in modality

The observed interactions between perceptual speed and word speed were only found when the modality of perceptual stimulus and verbal stimulus matched. Below I discuss two possible explanations for this finding: whether the perceptual stimulus and word can be integrated and the deployment of perceptual attention.

4.12.1.2.1 Integratibility

One view that may account for the finding that interactions are only observed when perceptual and verbal stimuli match in modality is Kaschak at al's (2005) notion of integratability. They argue that a mismatch advantage is more likely when a perceptual stimulus cannot easily be integrated into a simulation. For example, in Kaschak et al. (2005) responses to sentences were slower when the direction of motion of a visual stimulus matched the direction of motion described in the sentence than when they did not match. The authors argue that responses were slowed when the directions matched because the simple black and white images could not be integrated into the simulation of events in the sentence (i.e. of real-world objects in motion). In the present data, when the perceptual stimulus and word were presented in different modalities then they may have become two distinct events meaning that the perceptual stimulus could not be integrated into the word meaning. This explanation is not sufficient however because elsewhere effects of perceptual stimuli on words and effects of words on perceptual stimuli have been found when using stimuli of different modalities (e.g. Kaschak et al., 2005; Brunye et al., 2010). Further, the idea that two stimuli (perceptual stimulus and word stimulus) cannot be integrated into an event because they are of a different modality goes against what we know about action representations. Alaerts, Swinnen and Wenderoth (2009) showed that action representations are multimodal. Using TMS, excitability of the motor cortex was found to increase to congruent auditory and visual stimuli compared to stimuli in a single modality. A crucial factor in the integration of multiple modalities however is likely to be temporal overlap. For example, Brunye et al. (2010) presented footsteps (auditory) at the same time as participants read passages (visual) and found effects of footstep speed on reading time. In the experiments here, the perceptual stimulus was presented *before* the verbal stimulus, possibly reducing the likelihood of integration. If they had been presented simultaneously, results for Experiment 4-6 and 4-9 may have looked similar to the experiments in which modalities matched.

4.12.1.2.2 Perceptual attention

One account of the importance of modality match could be in terms of perceptual attention. Connell & Lynott (2014) found responses to words with strong visual meanings (e.g. *cloudy*) were facilitated in a lexical decision task and naming task where words were presented visually and words with strong auditory meanings (e.g. *noisy*) were facilitated in the naming task that involved an auditory representation of a word. This shows that attention can be differentially deployed to the visual and auditory modality and this can have consequences for processing. Although vision and audition are thought to have separate attentional resources (Treisman & Davies, 1973; Burr & Alais, 2006) it has been shown that selectively attending to one modality reduces the efficiency of processing stimuli in an unattended modality (Spence, Nicholls & Driver, 2001) and decreases activation in modality-specific areas (Kawashima, O'Sullican & Rolans, 1995). In the current experiments perceptual attention may be directed to the modality in which the word is presented as this is the most efficient strategy to respond quickly to the word. The consequence of attending preferentially in one modality could be that attention and perception in other modalities is reduced. Thus for visual vection with auditory words (Experiment 4-8), attention was directed to auditory information as the participant was listening for the word. This results in the visual stimulus being insufficiently processed (and vice versa for auditory footsteps and visual words). This account does not claim that the perceptual stimulus was not processed at all, but rather was not sufficiently processed for the speed information to affect the comprehension of the word. Although other studies have found crossmodal effects, speed is possibly a subtler dimension of motion (compare to direction for example) and may require more attention to be fully processed.

4.12.1.2.3 Match in modality: conclusion

It seems most likely that an account in terms of perceptual attention can explain the lack of interaction when modalities did not match. Participants selectively directed their attention to the modality in which the words were presented in, thereby reducing efficiency of perception in other modalities (Kawashima et al. 1995; Spence et al. 2001). This perceptual effect is likely to be stronger because the perceptual stimuli and word stimuli were presented consecutively and not simultaneously, thereby making it easier to ignore the irrelevant modality. Based on this explanation I cannot conclude that speed simulations are specific to the modality of presentation (e.g. that only visual simulations are produced when words are presented visually) because it seems possible that speed stimuli in other modalities would lead to interactions if the experimental conditions were different: for example, if perceptual stimuli and words were presented simultaneously, or if there were a secondary task that required perceptual attention to be divided across modalities.

4.12.2 What do speed simulations look like?

Facilitation of responses was found (match effect) for visual stimuli but interference (mismatch effect) was found for auditory stimuli. Below I discuss four speculative explanations for these differences in modality: integratability between perceptual stimulus and word meaning, negativity/threat of the footsteps sounds, overlap in features of perceptual stimuli and word meaning and perceptual dominance in speed words.

4.12.2.1 Integratability

Kaschak et al's (2005) idea of integratability, as explained in section 4.12.1.2.1, could be used to try to explain why the direction of interaction differed between visual and auditory stimuli: one kind of perceptual stimulus may be more integratable with the meaning of the word leading to facilitation, but the other might be less integratable leading to inference. An account of integratability could be applied to the null effects observed in this chapter (Experiments 4-2, 4-3, 4-5 and 4-7). The motion produced by these visual and auditory stimuli could not be integrated into the simulation of the speed verb because they were simple, abstract depictions of motion and were perceived as separate, unrelated events to the speed verbs. Visual vection and the sound of footsteps could be integrated into the simulation of speed verbs because they both produced experiences that are consistent with the real-world experience of the meaning of those verbs. This idea can explain the null effects but it does not explain the difference between facilitation and interference across experiments 4-4 and 4-8 because both perceptual stimuli are integratable into the speed event. In fact, footsteps are more integratable than vection because they are sounds taken from the real world, but in Experiment 4-8 this resulted in interference.

4.12.2.2 Footsteps as negative stimuli

There may be something specific about the auditory stimuli used that led to interference as compared to the visual stimuli that led to facilitation. As described in the previous section, the sound of footsteps may have a particular emotional or biological significance in alerting danger. This state of alertness or arousal could lead to avoidant behaviour to protect oneself from harm. Thus the interference effect observed for Experiment 4-8 with auditory stimuli could be a result of this avoidance behaviour. When verb speed matched footstep speed, the salience of the event may have increased and responses were slowed due to avoidance of danger inducing stimuli. A similar effect has been found for abstract emotional words (Vinson, Anderson, Ratoff, Bahrami & Vigliocco, 2011): positive, negative and neutral words were presented preconsciously using interocular suppression and participants were instructed to respond whether the presented word appeared above or below fixation when they became aware of it. They found that negative abstract words were significantly slower to emerge into consciousness than positive and neutral abstract verbs. An alternative explanation to avoidance is automatic vigilance (e.g. Estes & Adelman, 2008) whereby a slow response reflects a prolonged evaluation of negative stimuli. Evaluating a stimulus that appears negative is more beneficial to survival than avoidance, which could lead a fatal outcome. Either due to avoidance or vigilance, responses to auditory words following footsteps of a matching speed were slowed down.

4.12.2.3 Feature overlap

An alternative explanation for the difference between visual and auditory stimuli is in terms of feature overlap, rather than due to modality differences specifically. Consider the matching conditions in Experiment 4-8: the auditory footsteps matched each word both in terms of speed and in terms of the effector used in the described action. That is, to *run* or to *saunter* involves the use of feet, and hence would produce the sound of footsteps. For Experiment 4-4, although the visual stimulus created a sense of motion, it was not specific to full-body actions such as running. In fact, it was more similar to the type of motion a person experiences when in a car or on a train. Therefore, the visual stimulus of Experiment 4-4 matched the meaning of the verbs only in terms of speed and not specific features of motion such as the effector. When the perceptual and verbal stimuli matched in multiple features (i.e. speed and effector) as in Experiment 4-8, interference was more likely to occur because more resources were taxed; more resources were engaged in processing the perceptual stimulus so less were available for word comprehension. When only one feature was shared (i.e. just speed) facilitation was found because the partial overlap acted as a ‘head start’ to the processing of the word (note that although the speed of perceptual stimulus did match for the more abstract speed stimuli, since this speed was abstract and not biological or self-relevant then it most likely did not overlap with speed of the words). One can also appeal to Connell and Lynott's (2012b) account of attentional modulation. Although one may predict that both the visual stimuli and the auditory stimuli are comparable in terms of recruitment of perceptual attention, because they occur before word presentation, the account also describes attentional modulation at a feature-specific level. That is, the auditory stimulus will recruit a greater proportion of the attentional resources required for simulation than the visual stimulus because it shares more features. In Chapter 6 I further explore this hypothesis with sentences.

4.12.2.4 Perceptual Dominance

Finally, an account in terms of the dominance of perceptual modality could be plausible. The meaning of speed words may be strongly visual, with auditory information less salient. As in Connell & Lynott (2014) where responses to visual words were facilitated if the word's meaning was strongly visual, here if speed words are strongly visual responses to them may have been facilitated if preceded by a matching visual depiction of speed. When a speed word was preceded by a matching auditory speed stimulus, responses may have been slowed since the auditory speed needed to be converted into a visual depiction for a match to occur. This idea is in line with findings that show that switching between modalities when making perceptual judgments leads to processing costs (Pecher et al., 2003).

4.12.2.5 Modality differences: conclusion

An explanation in terms of feature overlap seems to be the most plausible. Modality is unlikely to explain the differences since previous experiments have found both facilitation and interference effects using auditory perceptual stimuli (Kaschak et al. 2005). An ecological avoidance or vigilance account is similarly not convincing since the footsteps were not particularly threatening sounding and did not appear to approach the listener, however it might be possible that the footsteps sounds increased arousal. Additionally, although world experience is generally visually dominant, there is no clear evidence that speed perception is. Since speed involves spatial (more efficiently processed with vision e.g. Howard & Templeton, 1966) and temporal (more efficiently processed with audition (Recanzone, 2003)) dimensions I am not convinced by a visual dominance explanation. Kaschak's (2005) intergratability account also fails to sufficiently account for the findings since I find an interference effect for the perceptual stimulus that is intuitively the most integratable (footsteps) into the described event.

4.13 Chapter conclusion

Using a lexical decision paradigm in which presentation of fast and slow verbs was preceded by presentation of a speeded perceptual stimulus I found an interaction between perceptual speed and word speed conditional on two factors: first, whether the perceptual stimulus was relevant to biological motion and second, whether the modality of perceptual and verbal stimuli matched. I propose that mental simulations for speed verbs involve biological motion processes and action preparation. This suggests that they are specific to the full meaning of the verbs (i.e. of an agent moving) instead of a more schematic speed depiction that is abstracted away from agents. The results also imply crucial factors that should be considered in an experimental paradigm designed to assess simulation: timing of stimuli presentation and attentional demands. These findings could also be interpreted as suggesting a strong role of context in mental simulations: there is likely to be many environmental and attentional factors that play a role in the extent to which simulations develop in service of language comprehension.

Chapter 5 Do speed verbs affect speed discrimination?

This chapter continues the investigation of speed verbs and the contribution of visual speed perception to comprehension. As described in Chapter 2, demonstrations of embodiment include the effect of visual stimuli on comprehension of words and sentences that describe visual features (e.g. Dudschig, Souman & Kaup, 2013; Meteyard et al., 2008; Kaschak et al., 2005). If understanding visual language requires simulations in visual areas of the brain, then processing visual stimuli should affect how visual language is comprehended, because both processes involve the same systems. I provided evidence for this effect with speed language in Chapter 4 whereby visual lines moving at a fast or slow speed affected comprehension of fast and slow verbs.

The proposal that we understand meaning by activating the brain's sensory systems also leads to the converse prediction that processing language about visual features will affect visual perception processes, or more specifically here, that processing language about speed will affect speed perception processes (the 'bidirectional hypothesis' (Aravena et al. (2011)). There is growing evidence for this reciprocal relationship between language and visual perception. Research conducted by Zwaan et al (e.g. Stanfield & Zwaan, 2001, Zwaan et al., 2002, Zwaan et al., 2004) using cross modal priming shows that simulations of sentence meaning include specific information about visual features that affects responses to pictures. Participants read sentences that described objects in a particular location, with the location implicitly modifying either the shape or the orientation of the described object, and then had to respond as to whether or not a presented picture was mentioned in the sentence. Picture responses were faster when the shape or orientation of the object in the picture matched that of the object described in the sentence, compared to when they did not, even though these features were never explicitly mentioned in the sentence.

As reviewed in Chapter 2, further evidence for the effect of language on visual processing can be found in imaging studies, showing that visual language activates visual processing areas of the brain (e.g. Pulvermüller & Hauk 2006; Simmons et al.

2007; Martin et al. 1995; van Dam et al. 2010). Despite the popularity of fMRI for the localization of cognitive functions, some have argued that the spatial resolution of fMRI does not allow one to define whether the regions activated are the same as those used in actual visual perception, or instead neighbouring regions that could have computationally distinct capabilities (Dils & Boroditsky, 2010). Further, from these activations language processing cannot be disentangled from imagery processes (Mahon & Caramazza, 2008).

An issue with many existing behavioural investigations in language and perception interactions is that they may not demonstrate an automatic effect of language on perception but instead occur via a more explicit, inferential process taking place *after* the meaning of the linguistic stimuli has been retrieved (see section 1.5.2, Chapter 1). This second process could easily be explained by a disembodied, modular theory of semantics in which semantics and perception are independent systems that do not interact during online processes (e.g. Mahon & Caramazza, 2008). In the cross-modal priming studies of Zwaan and colleagues (e.g. Stanfield & Zwaan, 2001, Zwaan et al., 2002, Zwaan et al., 2004), participants judge whether a picture matches the object described in a sentence, explicitly linking language with the visual percept. This task also involves other processes such as object recognition and short-term memory. It is possible then that these effects occur at later, higher-order processing stages, rather than in low-level visual perception areas, but this paradigm cannot distinguish between these different stages. Furthermore, using response time as a measure does not guarantee that the correct process is being measured because response time encompasses all stages of processes in a decision (Meteyard et al., 2007). Participants may (implicitly or explicitly) generate task based expectations that lead to facilitation/interference effects such as those observed in previous studies that could affect low-level visual processes. This would be evidence for a close relationship between language comprehension and non-linguistic tasks, but not evidence for embodied activations (Meteyard et al., 2007) including views falling within both the weak and strong end of the embodied continuum (Meteyard et al., 2012; see section 1.3.2.1. Chapter 1 and Figure 1-2). The question remains then whether the “high level” process of language comprehension can affect “low-level” perceptual processes that are putatively more rapid.

Preliminary evidence suggests that language comprehension effects in other semantic domains do engage low-level perceptual mechanisms. Using a similar crossmodal paradigm to Zwaan and colleagues (e.g. Stanfield & Zwaan, 2001, Zwaan et al., 2002, Zwaan et al., 2004), Hirschfeld, Zwitserhood and Dobel (2011) had participants read sentences and decide whether a presented picture was described in the sentence or not. The picture was either mentioned or not (e.g. *the ranger saw the duck in the lake*) and could be of matching or different shape (e.g. sitting duck versus flying duck). Using MEG, modulations in the response of occipital regions were found to reflect mismatch in object shape between pictures and sentences, as early as 120ms after picture onset. Thus, top-down semantic information affected visual processing at early stages.

Using methods and measures from visual perception research, such as signal detection theory or discrimination thresholds, can aid in drawing the boundary conditions of these embodied effects. These methods allow the visual processes that are engaged in language comprehension to be better defined by providing measures of perceptual performance that separate perceptual sensitivity from bias. Sensitivity is a measure of low-level perception describing one’s ability to separate perceptual signal from noise. Bias instead reflects one’s internal response criteria and is shown to be more susceptible to high-level influences (e.g. Morgan, Dillenburger, Raphael & Solomon, 2012).

Signal detection theory has been used in the embodied framework to address whether words referring to upwards and downwards motion affect visual direction perception (Meteyard et al., 2007; Pavan et al., 2013; Francken et al., 2014). Meteyard et al. (2007) used a threshold motion detection task in which participants indicated whether they saw motion or not in a visual stimulus containing random dot kinematograms (RDKs) whilst passively listening to motion verbs. At threshold levels of visible motion it was found that low-level visual motion detection, as measured by perceptual sensitivity (d'), decreased when heard motion verbs described motion in the same direction as that of the visual motion. Furthermore, measures of internal bias (or criterion (C)) were found to be lower for congruent stimuli than incongruent stimuli. This lower criterion suggests that participants were more liberal in deciding that coherent motion was present when words and direction of motion were congruent. Differences in decision criteria could be explained by modular theories (Fodor, 1983), where language and perception systems are separate, domain-specific systems. A modular theory would permit semantic and perceptual information to interact at later processing stages once a word is understood, but these theories could not account for effects in measures of sensitivity. Pavan et al. (2013) sought to further test the interaction found in Meteyard et al. (2007) in order to rule out any modular explanations. Using a modified version of the task in which participants had to decide whether they perceived upwards or downwards motion in random dot kinematograms (rather than coherent versus random motion), Pavan et al. (2013) parametrically varied the onset of the visual stimuli to be simultaneous with the presentation of the auditory word (0 ms) or 150, 450 or 1000 ms after word presentation. Results showed that direction discrimination sensitivity was higher for congruent stimuli compared to incongruent stimuli and that this difference was largest when the visual stimuli occurred 450 ms after word onset, the time at which semantic information from the word would be available. These results suggest that there are top-down influences from semantics to processes involved with motion perception. However, Francken et al. (2014) failed to find effects of visual language on perceptual sensitivity but instead found effects on criterion and response time measures. Further, using fMRI they localised the interaction of language and vision to the left middle temporal gyrus (lMTG), an area in the typical language network thought to be involved in integration of modality-specific information and lexical retrieval, rather than areas implicated in motion perception (e.g. hMT+). This suggests that embodied effects are happening at the semantic and not the perceptual level. One reason for the discrepancies between studies could be temporal details of presentation: both Meteyard et al. (2007) and Pavan et al. (2013) presented words and motion stimuli simultaneously, but Francken et al. (2014) presented a single word before each motion stimulus. Thus, the temporal overlap between language and perception may be a crucial factor.

Here I assess whether low-level language-vision interactions generalize across domains to speed words. I use a standard psychophysical methodology to test the prediction that listening to speed words will affect visual discrimination of speed. The prediction is that when hearing words that describe a certain speed visual regions activated maximally at fast or slow speeds will be activated and subsequently affect performance on the speed discrimination task. Here I use the method of constant stimuli (e.g. Johnston, Benton & Morgan, 1999) to test this prediction. In this method participants are familiarized with a sine wave grating moving at a fixed 'standard' speed and have to decide whether subsequent gratings are moving faster or slower. This type of stimuli is thought to activate early visual stages up to V1, in comparison to methods assessing global motion detection (Hietanen, Crowder, Price & Ibbotson, 2007) such as the RDKs used in Meteyard et al. (2008), which tap higher stages, predominantly area MT/hMT+ (Salzman, Murasugi, Britten & Newsome, 1992; Newsome & Pare, 1988; Rudolph & Pasternak, 1999; Schenk & Zihl, 1997). Whilst completing the task participants passively listen to fast and slow motion verbs. By presenting words simultaneously with the visual task I can test the effect of word speed on all levels of processing. This method provides two psychophysical measures: speed discrimination threshold that denotes the smallest difference in speed that a participant can reliably detect, and point of subjective equality, or perceived speed, that denotes the perceived speed of the standard grating. Using this method I can assess the effect of speed words on perceptual sensitivity (speed discrimination threshold) and decision criteria (perceived speed) (Morgan et al., 2012). If there is an interaction between speed words and low-level visual processes, effects should be seen in measures of speed discrimination threshold. Alternatively, should interactions occur at later processing stages then an effect should be observed in measures of perceived speed. Based on the interactive nature of the visual processing system, effects could be observed in both measures, with interactions in low-level sensory regions feeding forward to affect later decision processes.

To summarize, the present experiment builds upon the work conducted in Chapter 4 that provided evidence for speed simulation in word comprehension by assessing the converse effect: whether speed words affect visual perception. Further, these experiments test whether speed simulations are found in low-level sensory regions where speed perception takes place, or at later, decisional stages. Based on the results of Chapter 4, that responses to words were facilitated when the visual stimulus and word meaning matched in terms of speed (and not also details about effector), here I predict that performance in the speed discrimination task will be higher when there is congruency between word speed and standard speed. That is, performance should be better at slow speeds when listening to slow words compared with fast words, and vice versa with fast words.

5.1 Experiment 5-1: Fast, slow and neutral verbs

5.1.1 Method

5.1.1.1 Participants

4[5] participants (3 female, average age = 24.75, *SD* = 1.89) took part in the experiment for payment. All participants were psychology students (postgraduate or undergraduate), but none had significant experience with psychophysics experiments.

5.1.1.2 Materials

Visual stimuli were luminance-modulated sinusoidal gratings with a spatial frequency of 1 c/deg and a 50% Michelson contrast. Stimuli were presented on a CRT monitor (Mitsubishi Diamond Plus 230SB) with a refresh rate of 100 Hz and rendered online in Matlab using the Psychophysics toolbox extensions (Brainard,

[5] The number of participants here was low, which could mean the study was underpowered. However, this experiment can be viewed as a pilot, as based on the four participants changes in the design were implemented in Experiment 5-2.

1997; Pelli, 1997). Gratings could appear in 8 possible locations on screen in a notional circular aperture, 5 degrees from the centre. Gratings could move in either left or right direction, randomized over trials. Verbal stimuli consisted of 16 fast verbs (e.g. *dash*), 16 slow verbs (e.g. *amble*) and 16 motion verbs of neutral speed (e.g. *go*). See tables Appendix 1-1, 1-2 and 1-3 for list of verbs. Verbs had previously been rated in a norming study as to their speed, as described in Chapter 4, section 4.3.1.2.1. The verbal stimuli were recorded by a female speaker with an English accent, using Audacity. Slow verbs hade an average duration of 565 ms (SD = 75) and fast verbs had an average duration of 500ms (SD = 121). This difference was not significant (t (30) = 1.83, p = .08).

5.1.1.3 Procedure

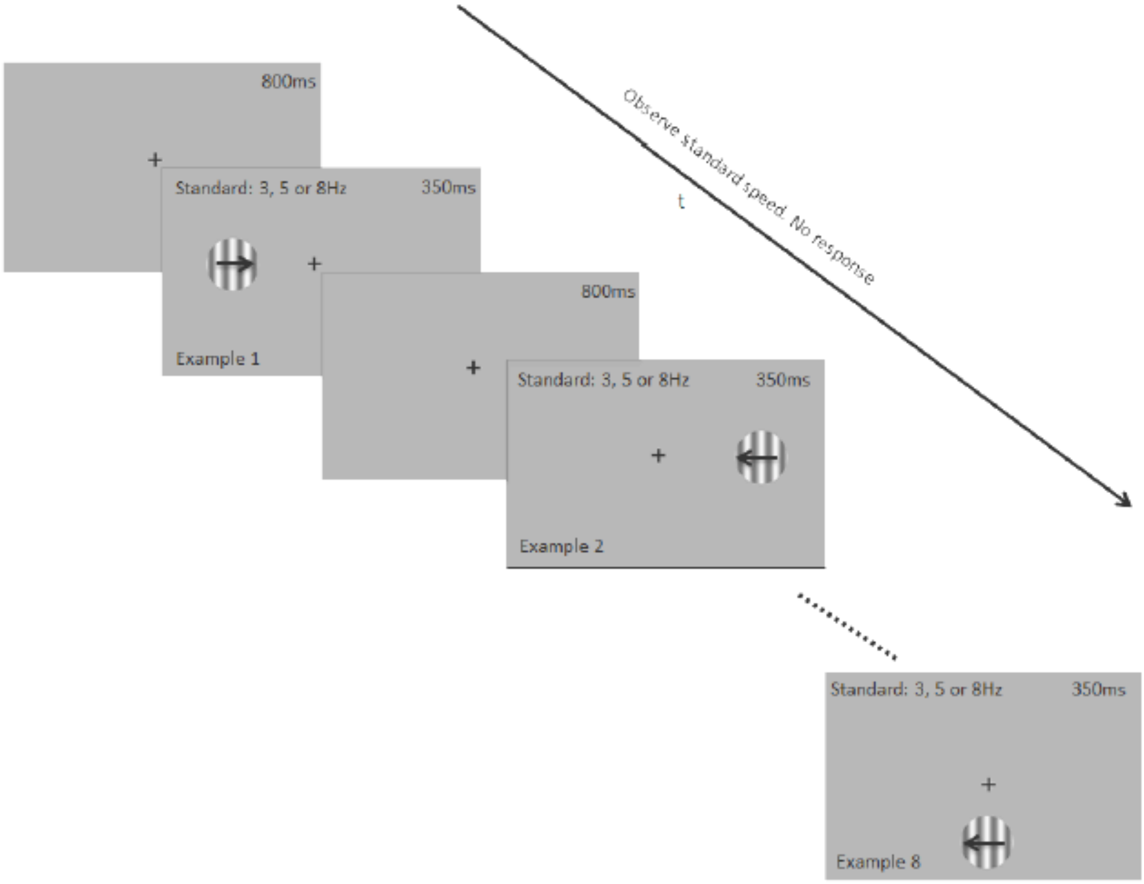
Participants were seated 57cm from the computer screen, using a chin rest, in a dark experimental room. On each run, participants were first shown 8 examples of gratings moving at the standard speed, one at each of the 8 possible locations. The standard speed could be 1, 2, 3, 5 or 8Hz. Gratings were shown for 600ms. Participants were instructed to fixate the centre of the screen and try to internalize the speed of the standard grating. Participants then completed 12 practice trials in which they had to decide whether subsequent moving gratings were moving faster or slower than the standard speed. Feedback was provided on all practice trials in order to establish an internalized memory for the standard speed.

A test phase followed the practice phase. The experimental task was the same ("faster or slower than standard speed?") in the two phases. However, in the test phase, no feedback was provided and participants passively listened to auditorily presented words, with a gap of 1500ms between each word. This duration was chosen so that the presentation of words did not appear to be either fast or slow. The presentation of word types was blocked so that within each run, only one word type was heard. I used five different standard speeds (1, 2, 3, 5 and 8 Hz) in different sessions, whereas the comparison speed (i.e., the speed of a single drifting grating in each trial) varied between 0.6 * standard speed and 1.4 * standard speed in seven steps (see Table 5-1) in order to generate a psychometric function (each psychometric function was built over 140 trials, i.e., 20 repetitions per each data point). Each comparison speed was repeated 5 times during each run. Each combination of word type and standard speed was ran 4 times, resulting in a total of 24 runs. Runs were presented pseudo-randomly so that the same standard speed did not appear consecutively. One run lasted approximately 3 minutes and the whole experiment lasted approximately 3 hours, which was divided into 3 separate sessions. At the beginning of each session, the participant completed one practice run which was thrown out. The participants were encouraged to take breaks throughout the experiment whenever they began to feel tired. Figure 5-1 illustrates the experimental procedure.

5.1.1.4 Data analysis

The first 5 trials of each run were removed from analysis. The data were fitted with cumulative Gaussian functions. The 50% point on the psychometric function (point of subjective equality) provided an estimate of perceived speed, whereas the discrimination threshold was defined as the width of the underlying Gaussian error distribution σ (corresponding to the difference between the 50% and the 84% points on the psychometric function). Analyses were conducted on point of subjective equality and speed discrimination threshold as a percentage of standard speed. A positive point of subjective equality arises when the standard speed is perceived faster than its true speed and a negative point of subjective equality arises when the standard speed is perceived slower than its true speed (a value of 0 would mean the standard speed was perceived veridically). For speed discrimination threshold, increasing values reflect decreasing performance on the speed discrimination task: larger differences in speed between the standard speed and comparison speed are needed for the participant to reliably detect a difference. Response times were also recorded. Each measure was tested with a repeated measure ANOVA with two factors: standard speed (1, 2, 3, 5, 8 Hz) and word speed (fast, slow).

A


800ms
Standard: 3, 5 or 8Hz
350ms
Example 1
800ms
Standard: 3, 5 or 8Hz
350ms
Example 2
Standard: 3, 5 or 8Hz
350ms
Example 8
Observe standard speed. No response
t

B

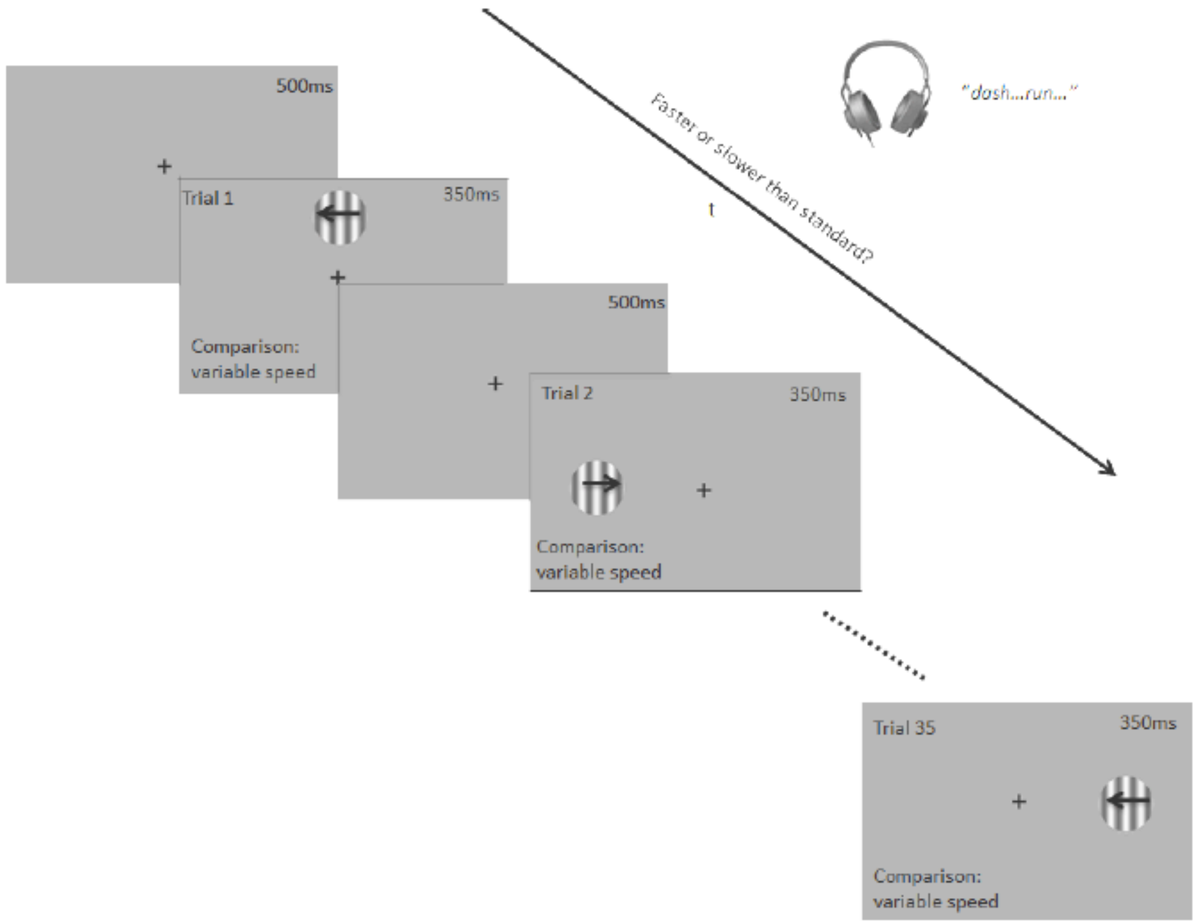


Figure 5-1. Experimental procedure. Participants first observe and internalize standard speed (A) and then on experimental and practice trials decide whether gratings are moving faster or slower than the standard (B) whilst listening to words.

Table 5-1. Comparison speeds used for each standard speed

Standard Speed (Hz)	Comparison Speeds (Hz)
1	0.6, 0.84, 0.94, 1, 1.06, 1.16, 1.4
2	1.2, 1.68, 1.88, 2, 2.12, 2.32, 2.8
3	1.8, 2.52, 2.82, 3, 3.18, 3.48, 4.2
5	3, 4.2, 4.7, 5, 5.3, 5.8, 7
8	4.8, 6.72, 7.52, 8, 8.48, 9.28, 11.2

5.1.2 Results

5.1.2.1 Speed discrimination threshold

Average speed discrimination values, as a percentage of standard speed, are displayed in Figure 5-2. There was a significant effect of standard speed (F (4, 12) = 34.91, p <. 001, η^2_p =. 92) such that speed discrimination threshold was higher for lower standard speeds. This was supported by a significant linear effect of standard speed (F (1, 3) = 59.11, p <. 01, η^2_p =. 95). An effect of standard speed is not relevant to the hypothesis of interest because it does not reflect any interaction with word speed. However it does suggest that the speed discrimination task may be more difficult at lower levels of standard speed. There was no effect of word speed (F < 1) and no interaction between standard speed and word speed (F < 1).

Thus there was no evidence to support my hypothesis in measures of speed discrimination threshold.

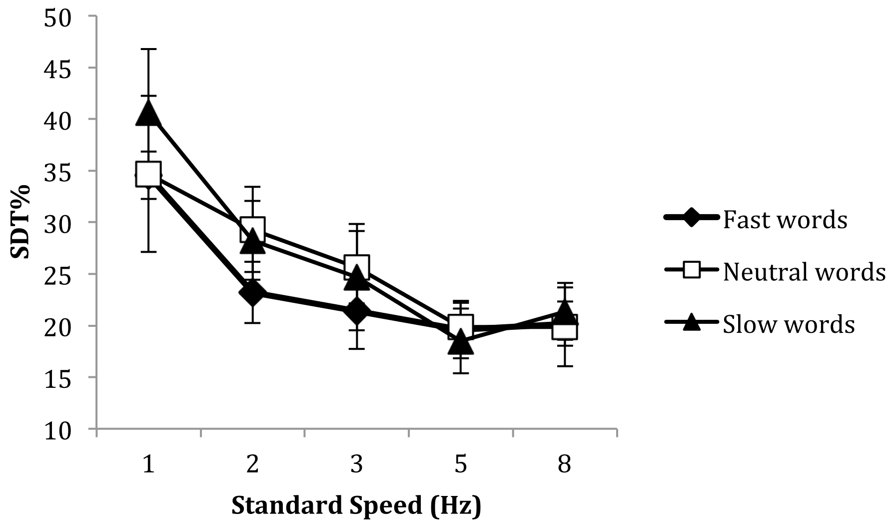


Figure 5-2. Average speed discrimination values, as a percentage of standard speed in Experiment 5-1. Error bars reflect 1 standard error.

5.1.2.2 Point of subjective equality

Average point of subjective equality values, as a percentage of standard speed are displayed in Figure 5-3. There was a significant effect of standard speed (F (4, 12) = 11.6, p <. 001, η^2_p = .79) in which perceived speed was higher for lower standard speeds. This was supported by a significant linear effect of standard speed (F (1, 3) = 26.72, p = .01, η^2_p = .9), however this is not theoretically relevant to the present hypotheses because it does not reflect any interaction with word speed. There was no effect of word speed (F <1) and no interaction between standard speed and word speed (F <1).

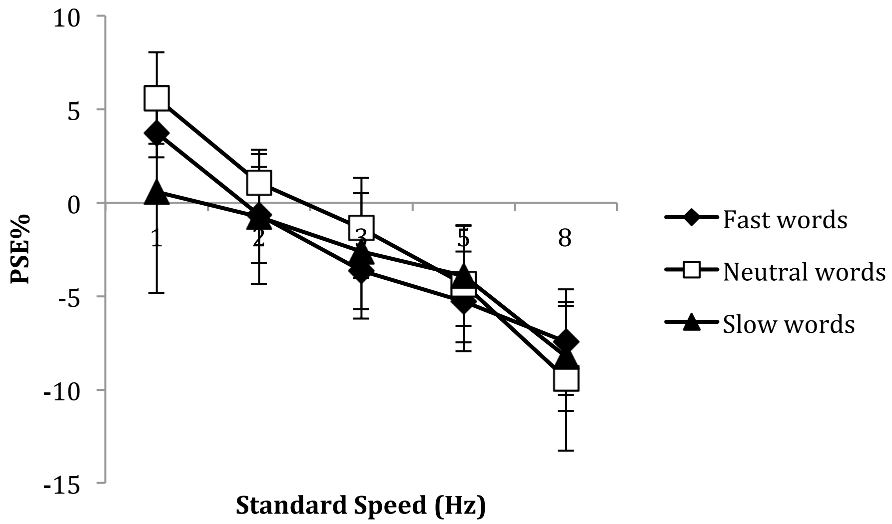


Figure 5-3. Average point of subjective equality values, as a percentage of standard speed in Experiment 5-1. Error bars reflect 1 standard error.

5.1.2.3 Response times

Responses for trials in which the comparison speed was the same as the standard speed were removed (14% of trials). Incorrect responses (27% of remaining trials) and responses outside 2.5 standard deviations of a participants mean response time were removed (less than 3% of correct responses).

I only analysed responses to 3, 5 and 8 Hz (overall accuracy for 1 and 2Hz was less than 75%). A 3 (standard speed) X 3 (word type) within subjects ANOVA was used. I found no effect of standard speed (F <1), no effect of word type (F (2, 6) = 2.53, p = .16, η^2_p = .46) and no interaction between standard speed and word type (F (4, 12) = 1.39, p = .3, η^2_p = .32) in response time. Mean response times are displayed in Figure 5-4.

I decided to divide responses into "faster" responses (when the comparison grating was moving faster than the standard speed) and "slower" responses (when the comparison grating was moving slower than the standard speed), because the relative speed of the comparison stimulus to the standard stimulus may also be a factor that interacts with word speed.

For “faster” responses, a 3 (standard speed) X 3 (word type) within subjects ANOVA found no effect of standard speed (F<1), no effect of word type (F<1) and no interaction between standard speed and word type (F<1). Mean “faster” response times are displayed in Figure 5-5.

For “slower” responses a 3 (standard speed) X 3 (word type) within subjects ANOVA found a main effect of word type (F (2, 6) = 9.42, p = .01, η^2_p = .76) with a Bonferonin-corrected alpha level of .025, for dividing responses into ‘’faster’’ and ‘”slower’’ post-hoc. 2-tailed t-tests showed that response times during slow words were faster than during fast words (t (3) = 3.75, p = .03, d = 2.17) and faster than during neutral words (t (3) = 2.38, p = .1, d = 1.37), but this was not significant according to the corrected alpha level. There was no difference in response times during fast words and during neutral words (t (3) = 2.06, p = .13, d = 1.19). This result suggests that responses are facilitated when the speed of words matches the speed of the comparison (i.e. whether the comparison speed is “faster” or “slower”), for “slower” responses only. However, as inferred from the graph, this effect only occurs at 5Hz and 8Hz, but not at 3Hz. There was no effect of standard speed (F<1) and no interaction between standard speed and word type (F (4, 12) = 1.73, p = .21, η^2_p = .37). Mean “slower” response times are displayed in Figure 5-6.

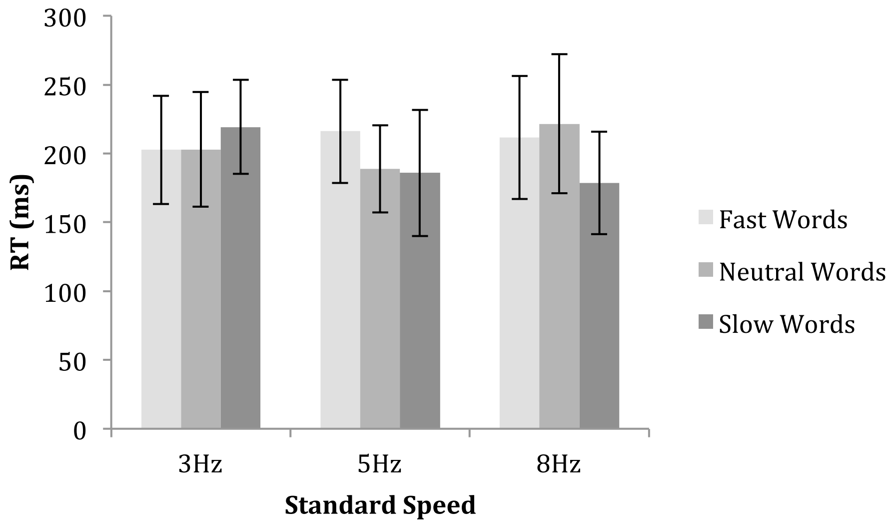


Figure 5-4. Average response time in Experiment 5-1. Error bars reflect 1 standard error.

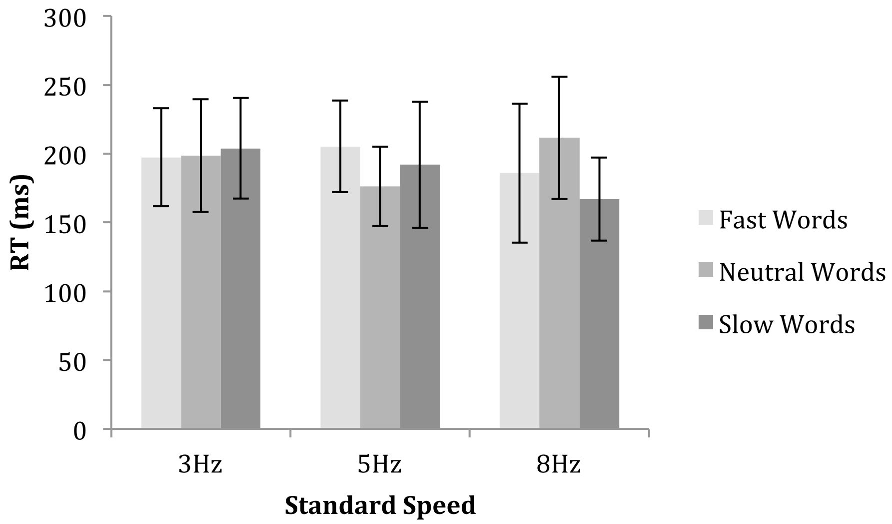


Figure 5-5. Average response time for "faster" responses only in Experiment 5-1. Error bars reflect 1 standard error.

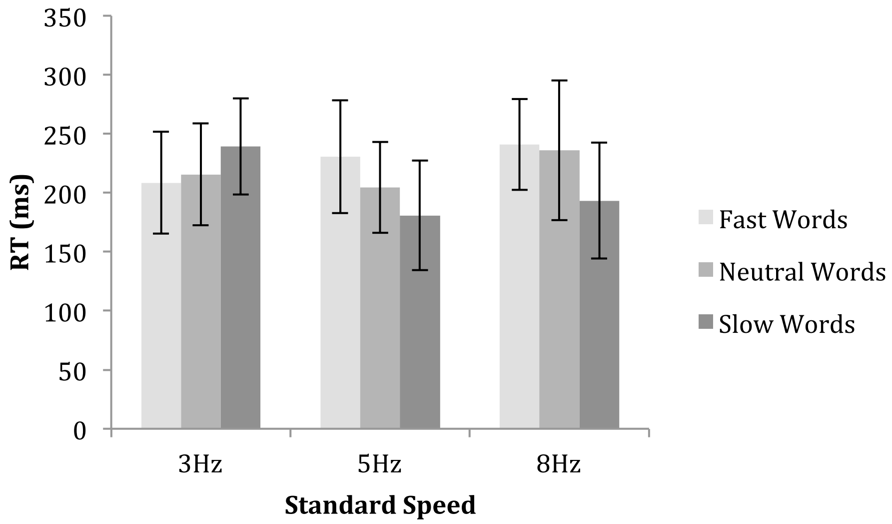


Figure 5-6. Average response time for "slower" responses only in Experiment 5-1. Error bars reflect 1 standard error.

5.1.3 Discussion

Experiment 5-1 did not find any effect of word type on psychophysical measures but did find an effect on measures of response time. This suggests that processes involved in comprehension of speed words and visual perceptual processes may not interact at low levels of perception, but instead during higher order response decisions.

Before discussing the implications of this result I decided to address some problems with the current design. Experiment 5-1 was very long and this may have had an adverse effect on the effectiveness of the verbal stimuli for two reasons. First, participants became sleepy and attention towards the spoken words may have been limited. Second, it is possible that retrieval of the meaning of the words was reduced the more each word was repeated. This effect is known as semantic satiation (e.g. Smith & Klein, 1990). Therefore, in Experiment 5-2 the length of the experiment was reduced. This was achieved by removing the neutral motion word-type because it was not crucial to the hypotheses (the comparison of interest was between fast and slow verbs). The number of standard speeds was also reduced to three (3, 5 and 8Hz) based on the very low accuracy for 1 and 2Hz in Experiment 5-1 (< 75%).

Additionally the duration of gratings was reduced to 300ms as subjects in Experiment 5-1 had been responding more quickly than 600ms and some participants commented that the presentation was too slow.

5.2 Experiment 5-2: Fast and slow verbs only

5.2.1 Method

5.2.1.1 Participants

7[6] participants (6 female, average age = 24.43, *SD* = 2.57) took part in the experiment for payment. All participants were psychology students (postgraduate or undergraduate), but none had significant experience with psychophysics experiments.

5.2.1.2 Materials

Visual and verbal stimuli were identical to Experiment 5-1 except that the verbs of neutral motion were removed as well as standard speeds of 1 and 2Hz.

5.2.1.3 Procedure

The procedure was the same as Experiment 5-1 except that now gratings were shown for 300ms (half as long). As the experiment now used only fast and slow verbs and standard speeds of 3, 5 and 8Hz, the number of runs was reduced to 24, with the whole experiment lasting approximately 1.5 hours, divided into 2 separate sessions.

5.2.2 Results

No effects or trends were found in response time for Experiment 5-2 and so will not be discussed further.

[6] Again, this study may be underpowered. Meteyard, Bahrami & Vigliocco (2007) used 20 participants in their motion detection task. Note however that when Experiment 5-2 and 5-3 are combined, results remain the same.

5.2.2.1 Speed discrimination threshold

Average speed discrimination threshold values as a percentage of standard speed are displayed in Figure 5-7. There was no effect of standard speed (F <1), no effect of word speed (F (2, 12) = 2.21, p = .15, η^2_p = .27) and no interaction between standard speed and word speed (F<1).

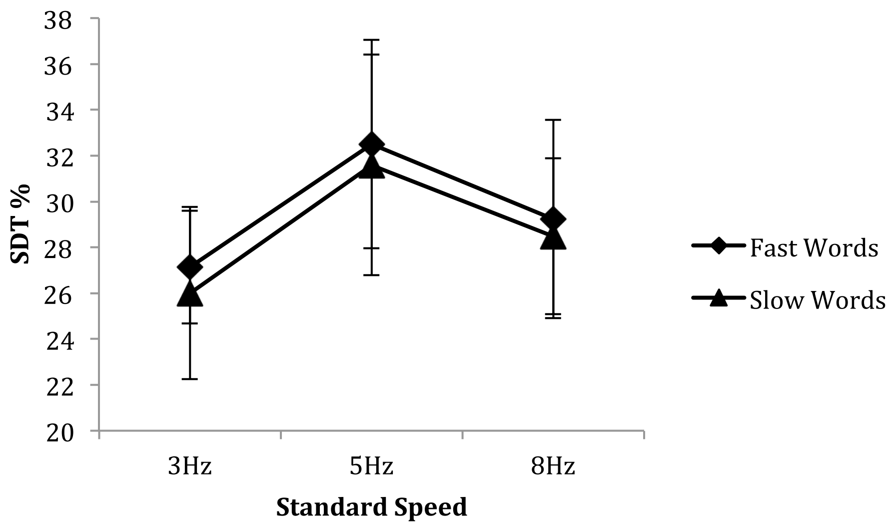


Figure 5-7. Average speed discrimination thresholds as percentage of standard speed for Experiment 5-2. Error bars reflect 1 standard error.

5.2.2.2 Point of subjective equality

Average values of perceived speed as a percentage of standard speed are displayed in Figure 5-8. A significant main effect of word type was found (F (1, 6) = 10.3, p = .02, η^2_p =. 63) such that perceived speed was overall lower for fast words than slow words. Planned comparisons found perceived speed was significantly lower for fast words than slow words at a standard speed of 3Hz (t (6) = 2.64, p =. 04, d = .99) but not at a standard speed of 5Hz (t (6) = .72, p = .51, d = .29) or 8Hz (t (6) = 1.18, p = .28, d = .48). That is, at 3 Hz, the standard speed was perceived as moving more slowly when listening to fast words compared to slow words. There was no effect of standard speed (F <1) and no interaction between standard speed and word speed (F (2, 12) = 1.67, p = .23, η^2_p =. 22).

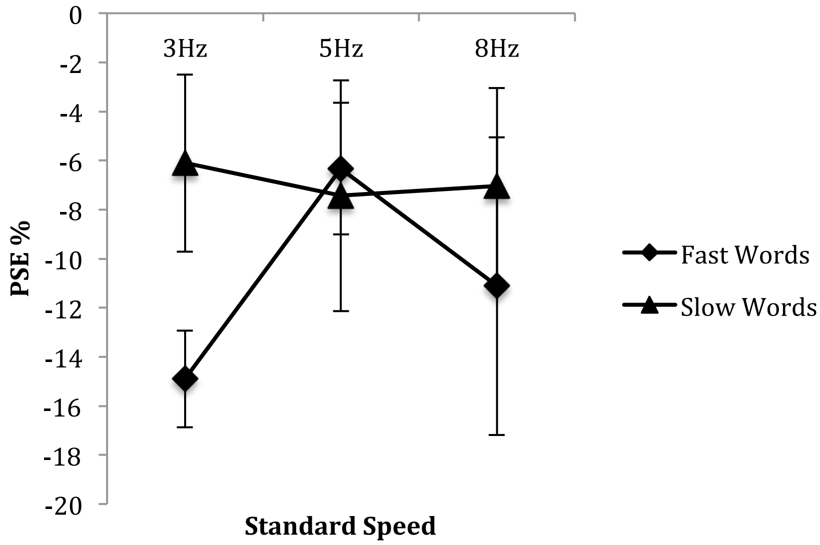


Figure 5-8. Average point of subjective equality values as a percentage of standard speed for Experiment 5-2. Error bars reflect 1 standard error.

5.2.3 Discussion

Results show that listening to speed words interferes with speed discrimination, as measured by perceived speed of the standard grating when discriminating between moving gratings of slow speeds (standard speed of 3Hz) but not between moving gratings of faster speeds (standard speed of 5Hz and 8Hz). This suggests that interactions between meaning inferred from the speed words and visual speed occur at later decisional processes (perceived speed), but only under certain conditions.

Before discussing implications of the results I decided to directly replicate Experiment 5-2 in Experiment 5-3 with a new set of participants, since the effect was not found in Experiment 5-1. This would make sure that the observed pattern is reliable.

5.3 Experiment 5-3: Replicating Experiment 5-2

5.3.1 Method

5.3.1.1 Participants

10 participants took part in the experiment for payment (6 females, average age = 24.3, *SD* = 3.13). Seven participants were postgraduate psychology students with no significant experience with psychophysics experiments. The remaining 3 participants were taken from the UCL psychology subject pool. One participant was removed for accuracy less than 50%.

5.3.1.2 Material and Procedure

All material and the procedure were identical to Experiment 5-2.

5.3.2 Results

5.3.2.1 Speed discrimination threshold

Average speed discrimination threshold as a percentage of standard speed is displayed in Figure 5-9. There was a significant main effect of standard speed (F (2, 16) = 4.17, p = .04, η^2_p = .34) such that speed discrimination threshold was higher for lower standard speeds as confirmed by a significant linear effect of standard speed (F (1, 8) = 5.46, p = .05, η^2_p = .41). There was no effect of word type (F<1) and no interaction between standard speed and word speed (F (2, 16) = 2.52, p= .14, η^2_p = .24).

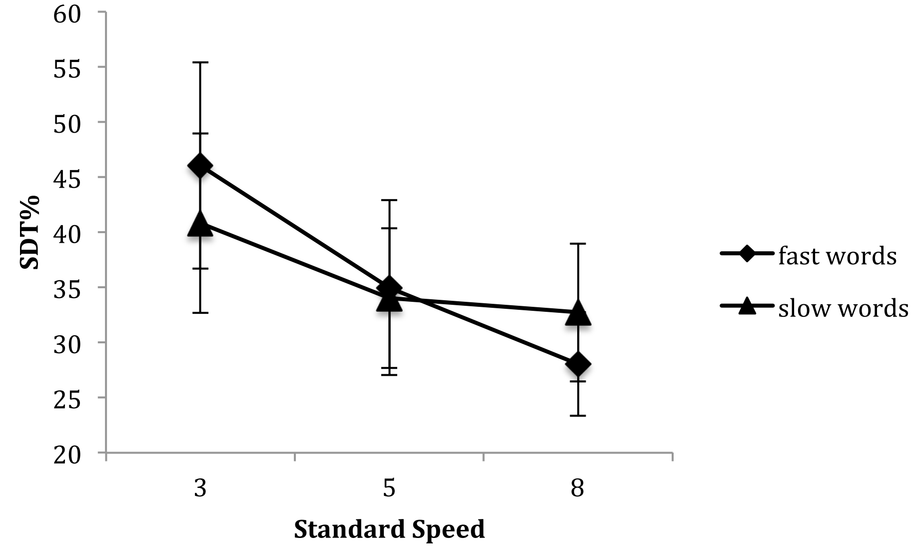


Figure 5-9. Average speed discrimination threshold as percentage of standard speed for Experiment 5-3. Error bars reflect 1 standard error.

5.3.2.2 Point of subjective equality

Average values of perceived speed as a percentage of standard speed are displayed in Figure 5-10. A significant main effect of word type was found (*F* (1, 8) = 10.49, p = .01, η^2_p = .57) such that perceived speed was overall lower for fast words than slow words. Planned comparisons found perceived speed was significantly lower for fast words than slow words at a standard speed of 3Hz (t (8) = 2.4, p = .04, d = .8) but not at a standard speed of 5Hz (t (8) = 1.78, p = .11, d = .63) or 8Hz (t <1). Thus, participants perceived the standard speed as slower when listening to fast words compared to slow words when the standard speed was 3Hz. There was also a significant effect of standard speed (*F* (2, 16) = 8.07, p = .004, η^2_p = .5), such that point of subjective equality was higher for lower standard speeds as confirmed by a significant linear effect of standard speed (*F* (1, 8) = 8.05, p = .02, η^2_p = .5). There was no interaction between standard speed and word speed (*F* (2, 16) = 2.32, p = .13, η^2_p = .23).

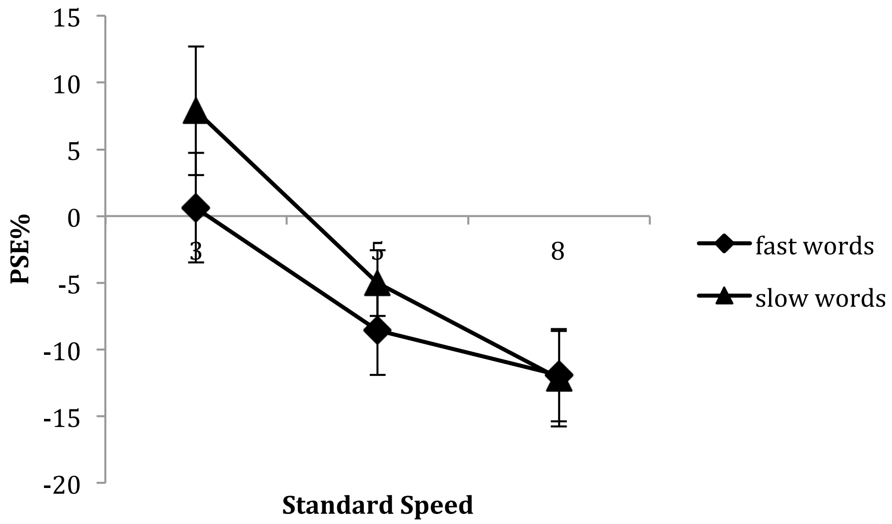


Figure 5-10. Point of subjective equality as percentage of standard speed for Experiment 5-3.

5.3.3 Discussion

Results show that listening to speed words interfered with visual speed discrimination processing of moving gratings at slower speeds only (standard speed of 3Hz). The effect of word speed was only observed in measures of perceived speed and not speed discrimination threshold. Listening to fast words lowered the perceived speed of the standard grating compared with listening to slow words when the standard speed was 3Hz but not when it was a greater speed of 5Hz or 8Hz. This suggests that speed words reliably interact with visual speed processing at decisional levels only and not at levels of perceptual sensitivity.

5.4 General Discussion

The aim of the experiments presented here was to assess the level at which visual speed information interacts with semantic speed information of words. Participants completed a visual speed discrimination task at the same time as passively listening to fast and slow motion verbs. In Experiment 5-1 I failed to find an effect of word speed on speed discrimination measures but did find an effect in response time for "slower" responses only. This led to the suggestion that speed in language affects visual processes only via top-down processes from high-level semantic areas. An alternative explanation for this effect is that the experiment was too long with words repeated multiple times, leading to reduced activation of speed-related meanings. I tested this idea with a modified version of the experiment that was significantly shorter. Using the shorter experiment, with two separate sets of participants I have shown that listening to words describing fast and slow motion affects speed discrimination processes. Specifically there was an effect of word speed on point of subjective equality. When passively listening to words that describe fast and slow motion and performing a speed discrimination task with a slow standard speed (3Hz), the perceived speed of the standard was affected: perceived speed was slower after listening to fast words than after listening to slow words. In both experiments this effect was observed at 3Hz only. Overall results suggest that word speed affects decisional stages of visual perception (perceived speed) however there were no effects on perceptual sensitivity (speed discrimination threshold), supporting the view that interactions between word meaning and perception occur at higher processing levels.

Thus, how do speed words affect the perceived speed of the standard stimulus? One explanation is that participants are more likely to respond in the opposite direction of the speed implied by the verb, because they attribute any matching speed to the verbal stimuli and not the standard speed stimuli. Francken et al (2014) suggest that language-vision interaction may be mediated by the left middle temporal gyrus (lMTG), a semantic area involved in the integration of modality-specific information as well as lexical retrieval. Thus, one explanation for the present data is that the speed of the comparison stimuli and the speed of the word were integrated. Here word speed would have affected how fast/slow the comparison was perceived. For example, when hearing words like "*run dash* etc.…" the fast speed implied by the verbs was integrated with the moving gratings, increasing the probability that the participant responded "faster".

Results do not show an effect of word speed on perceived speed at all standard speeds, but only when the standard speed is slow. It is likely that performance on the task is most difficult at 3Hz, making the stimuli more vulnerable to influence from other top-down processes. Speed discrimination is poor at the extremes (i.e. at extremely fast or slow speeds) (De Bruyn & Orban, 1988). In the current experiment I chose three standard speeds that were thought to cover a wide enough range of speed (from slow to fast) without it being too difficult for the participants to complete the task. It may be the case though that 3Hz is closer to the extreme slow end of the continuum than 8Hz is to the extreme fast end. Furthermore, discrimination performance is optimal for higher speeds when stimuli are presented at greater eccentricities but the reverse is true for slower speeds, which instead benefit from central presentation (Maunsel & van Essen, 1983). Both pieces of evidence point to increased difficulty at a standard speed of 3Hz. Here perception of the standard is more fragile because the gratings were presented in the periphery. Due to its fragility, it is more susceptible to influence from other processes, such as semantics. Results from Pavan et al. (2013) support the view that semantic information is more likely to interact with perception when the sensory signal is reduced or the task is more difficult. In their direction discrimination task, listening to direction verbs affected perceptual sensitivity when the visual stimuli were presented at threshold but not when presented at suprathreshold. Pavan et al. (2013) describe this process as “cross-modal compensation”, that allows “a processing system (vision) to harness information from other brain systems (linguistic semantics)”. When the processing system is already performing sufficiently it can work in a “more autonomous manner”. The effect of speed words on duration estimation shows a similar pattern to that found here. In Zhang, Jia & Ren (2014) participants had to decide whether the duration of a presented speed word was closer to 400ms or 1200ms. Fast words were perceived as longer than slow words when the actual duration of the presented word was 800ms, but not at other comparison durations (800ms is exactly halfway between 400 and 1200ms and therefore reflects the most difficult condition of the experiment). The extent to which the visual system is vulnerable to information from other systems could therefore be determined by contextual and task factors, such as task difficulty.

Evidence from speech perception supports the view that perceptual processes are more easily influenced under conditions of uncertainty or ambiguity (i.e. difficult conditions). Watching a speaker's lip movements has been shown to enhance speech comprehension, and particularly in noisy environments (Sumby & Pollock, 1954; Erber, 1969; Ma, Zhou, Ross, Foxe & Parra, 2009). Comprehenders rely more heavily on visual information as the signal to noise ratio increases (Erber, 1969). This effect has been termed "inverse effectiveness" (IE) (Ma, Zhou, Ross, Foxe & Parra, 2009; Senkowski, Saint-Amour, Hofle & Foxe, 2011). IE describes how a process is maximally enhanced by multisensory information when the unisensory stimulus is at its weakest. Based on this evidence, I cannot rule out the possibility that the effect of speed words on perceptual sensitivity (and not simply bias) could be observed using different tasks or contexts. For example, sensitivity effects could be found by making the speed discrimination task more difficult. Manipulations of the linguistic stimuli may also lead to greater simulations: using narratives instead of single words could lead to more of a global meaning structure and a greater exposure to the meaning (Dils and Boroditsky 2010). Based on the findings from Chapter 4 that suggest that mental simulations include specific information about biological motion, here by manipulating the visual stimuli to be more similar to the type of motion described by the verbs, word speed may affect the speed discrimination process more strongly.

The present results are problematic for strongly embodied as well as unembodied theories of semantics (see Meteyard et al. (2012) for continuum of embodiment and Chapter 1, section 1.3.2.2.). Unembodied theories view semantics and perception as completely separable systems that are unable to interact. Strongly embodied theories propose that semantics *is* sensory information and would therefore predict that interactions *would* be observed at low-levels of perceptual processing. The results seem most compatible with a weak version of embodiment in which semantic and sensory information interact in regions of integration (e.g. lMTG) that are located in 'language regions' rather than perceptual regions (Francken et al., 2014), or in convergence zones, near to but not in primary sensory regions (e.g. Barsalou, 1999a).

Secondary embodiment cannot be completely ruled out with the current data; however there are some suggestions as to why it should not be considered. It seems unlikely that associative connections between semantics and perception would be powerful enough to affect performance on a psychophysics task that is very demanding, particularly when the linguistic stimuli are repeated several times and only passively perceived.

Rather than seeing the current data as support for weak but not strong embodied theories in general, results can be seen as support for a weak theory of embodiment for *speed* language specifically. Previous studies have found evidence for word effects on perceptual sensitivity (Meteyard et al. 2007; Pavan et al 2013) for directional verbs. Since direction is more concrete than speed it could be the case that it is more strongly embodied than speed. In the real world, direction appears to be more easily perceived, interpreted and described than speed due to speed being continuous, relative and a more complex perceptual feature (Lingnau et al., 2009). As a clearly defined and salient property of the world, direction may be more easily, or more necessarily, grounded.

In relating the work in this chapter to that of the previous, I have shown that in addition to perceptual speed affecting comprehension of speed words, the converse effect is also true: speed words affect perception of speed. In a similar way to how low-level, abstract perceptual speed does not affect comprehension of speed words, here interactions between semantic and perceptual speed do not occur at low-level sensitivity processing levels. Here however, I do find effects using abstract visual stimuli (moving gratings), but did not when investigating the effect of visual stimuli on verb comprehension in Chapter 4. Although these two findings seem at odds with each other, in the present experiment verbal and visual stimuli overlapped in time, whereas in Chapter 4, visual stimuli occurred *before* verbal stimuli. Further, the present tasks involves categorizing stimuli as “faster” or “slower” thereby providing a semantic interpretation for the visual stimuli that was not given in Chapter 4. Based on these factors then, the visual and verbal stimuli here overlapped to a greater extent both in terms of time and semantic features than the abstract stimuli in Chapter 4 thus created greater potential for interaction.

5.5 Chapter conclusion

This chapter complements the work reported in Chapter 4 that showed that perceptual speed affects speed verb comprehension by investigating the reverse effect: the effect of speed verbs on perception of speed. Further, the experiments investigated at what level of perceptual processing interactions with language occur. Listening to speed verbs affected performance on a speed discrimination task at the level of perceptual decision and not perceptual sensitivity. Results are in line with a theory of weak embodiment in which simulation of sensory information occurs in secondary sensory regions. Following from Chapter 4, the work here highlights another important factor that affects embodied simulations: task difficulty. Interactions between language and sensorimotor stimuli appear to be more likely when one task is particularly difficult, and thereby more open to influence from other processes. In addition, Experiment 5-1 further highlights the effect of context of embodied effects: when the experiment was long and words were repeated many times, no psychophysical effects were observed, only differences in response times. When the experiment was shortened, effects were observed in perceived speed. This suggests that the extent to which sensorimotor systems are recruited is dependent upon depth of processing and attentional factors.

Chapter 6 The influence of speeded actions and perceptual speed on comprehending sentences about fast and slow events

Chapters 4 and 5 provided evidence for multimodal activation during the processing of speed presented as single words. In this chapter I move forward in the investigation by exploring speed simulation in sentence comprehension. Using a similar experimental paradigm to that of Chapter 4, I combine speeded sensorimotor experience with sentences that describe speed of motion/action (e.g. "*The professor* stormed/sneaked *down the corridor*") and test for interference/facilitation effects in accuracy and response time for sentence sensibility judgments (reading a sentence and deciding if it makes sense or not). Using sentence sensibility judgments is the most appropriate method here as it requires participants to fully comprehend sentences and therefore access sentence meaning without having to make explicit judgments about semantic features (and thereby draw attention to the features being investigated).

In speed sentences, one might expect a larger contribution of sensorimotor simulation than with single speed words since comprehension will require building a mental representation (Johnson-Laird, 1983), or situation model (Zwaan, 2004), of an event and assigning speed to specific agents in specific situations. Sentences reflect token representations and are therefore more constrained and specified than single words (Meteyard, 2008). In speed sentences, speed is not abstracted away from an event, as is the case for single verbs, but forms a component of an integrated event, giving it a more concrete meaning. The sentence context also removes any ambiguity about the verb. For example, the verb *bolt* could be interpreted as the noun *bolt* without any context, but in a sentence such as "*The man bolted out of the room*" the potential for misinterpretation is eliminated. Alternatively, one could reasonably predict that simulation of speed will be reduced for sentence comprehension compared to single word comprehension. In comparison to single words, the situation model built from comprehension of the sentence will include a variety of other attributes such as agents and goals and their features, which could weaken or wash out the simulation evoked by a speed verb. In addition, in line with the Linguistic Focus Hypothesis (Taylor & Zwaan, 2008) that suggests simulation occurs only when an action is within linguistic focus and not when the focus switches to another aspect of an event, speed simulation may occur only for the verb itself. By using a measure that assesses whole sentence comprehension we may lose the sensitivity to detect this. Bergen et al. (2007) argue however that mental simulations develop only when the meanings of single words are integrated into a larger sentence structure and not for lexical associations of words alone, suggesting that speed simulations should be observed for sentences. Moreover, previous studies have shown that behavioural methods can reveal motion simulations for sentences, including simulations of motion direction in the visual (Kaschak et al. 2005; Zwaan et al. 2004), auditory (Kaschak et al. 2005) and action domain (Glenberg & Kaschak, 2002; Glenberg, Sato & Cattaneo, 2008).

This chapter also adds to the thesis investigation by examining speed in different types of actions. I used four types of speed sentences: (1) full body speeded actions (speed verbs); (2) hand/arm speeded actions (speed verbs); (3) concrete actions with speed adverbs; (4) and abstract actions with speed adverbs. Sentence type 1 includes verbs of the same type as those used in Chapters 4 and 5. Here full body actions are described in which speed is encoded via the verb (i.e. the action and speed are combined in a single word), e.g. "*The professor* stormed/sneaked *down the corridor*". Sentence type 2 includes actions that are performed with the hand/arm. Again, here the type of action and the speed of action are both encoded within a single verb, e.g. "*Amy* stroked *her chin as she tried to remember*" versus "*Sarah* smacked *her head when she started to forget*". In sentence types 3 and 4 speed is encoded in adverbs that modify concrete or abstract actions that do not imply speed e.g. "*John* speedily/awkwardly *rolled up the sleeping bag*" and "*Bob* speedily/awkwardly *thought over the business plan*". By including four different types of speed sentences I can assess whether simulation of speed is a general effect or whether it is specific to certain types of actions and whether the nature of the simulation differs for different types of actions. Speed in full body actions may be more salient than speed in hand/arm actions because they more strongly imply movement over a spatial distance whereas hand actions more strongly emphasise completion of a task or act (e.g. compare "*Daniel rambled through the forest*" with "*Dave swung his bat toward the ball*"). It is also likely that there are temporal differences in the development of the simulation between full body and hand action simulations due to the action dynamics: rambling through a forest may involve simulating an action at a consistent speed for a lengthy duration but hitting a ball with a bat may involve simulating the quick swing of the bat as well as slower movements of action preparation. There may also be differences in the nature of the simulation in terms of the effectors and the type of posture involved.

Including sentence types 3 and 4 addresses simulation of speed when speed information is not encoded in the verb of action, but instead in a modifying adverb. The adverbs alone do not specify any information about the type of action, only the manner in which an action is executed (i.e. quickly or slowly). Since the speed information is not strongly tied to the action (i.e. it is encoded in a separate word), speed simulation could be weaker than when speed is encoded within the action verb. Alternatively speed information might be more salient because it is not hidden amongst other features of a verb but presented alone in the adverb. Finally, by assessing sentences containing adverbs paired with concrete actions (e.g. "*John* speedily/awkwardly *rolled up the sleeping bag*") and adverbs paired with abstract actions (e.g. "*Bob* speedily/awkwardly *thought over the business plan*"), I can test whether speed simulations are specific to concrete speeded actions or whether they are also recruited to understand abstract speeded actions. As described in Chapter 1, embodied approaches often face difficulty when posed with abstract concepts. One way in which abstract concepts could be embodied is via the use of metaphor: grounding abstract language in more concrete meanings. For example, comprehending a word like *argue* could involve the activation of a vertical spatial metaphor (Richardson, Spivey, Barsalou & McRae, 2003). However, some researchers argue that embodied simulations occur for the literal meaning of sentences only and not non-literal meanings (Bergen et al., 2007). For example, literal sentences describing up- or down-related meaning (e.g. *The cellar flooded*) interfered with a concurrent object categorization task when the object appeared in the same part of the visual field as that described in the sentence, but non-literal versions of the sentences (e.g. *The market sank*) did not (Bergen et al., 2007). Here I can test whether fast and slow abstract sentences are understood by grounding those abstract actions in concrete action simulation of speed.

To test speed simulation in sentences, I combined a sentence comprehension task with a manipulation of auditory speed and physical speed. Each manipulation is presented separately below.

6.1 Experiment 6-1: Manipulating Auditory Speed with Footsteps

In Chapter 4 I showed that listening to fast and slow footsteps affected response time to fast and slow verbs, with responses slower when speed of footsteps matched speed of verb compared to when they did not match. Here I used the same footsteps stimuli to test the effect of auditory speed on comprehension of sentences describing speed. Footstep sounds have also been shown to successfully imply speed in other studies (Brunye et al., 2010): fast footsteps led to faster reading time of route descriptions and larger distance estimations than slow footsteps.

In order to maximize the potential for interaction between perceptual speed and speed in sentences, footsteps were played before and during the visual presentation of the sentences. Sentences take longer to process than single verbs so by presenting the footsteps simultaneously with the sentences the footsteps will be active at the point when speed information is extracted from the sentence. Additionally, speed information occurs at different points of the sentence across the four sentence types so this will ensure that the overlap of footsteps and speed information in the sentences match. This method is also comparable to that of Kaschak et al. (2005) in which directional white noise was played simultaneously with sentence presentation.

Processing the sound of fast and slow footsteps whilst simultaneously completing a sentence task may affect some sentence types more than others due to shared features between the stimuli and the simulation. The sound of footsteps is more closely related to sentences that describe full-body actions than those that describe hand actions: footsteps reflect the sound made from full body actions. It could therefore be predicted that the speed of footsteps will only affect responses to sentences about full-body actions because it is not relevant to the simulation of hand actions. However, fast and slow footsteps may be processed in terms of a more general or abstract speed representation that overlaps with regions involved in comprehending speed in any sentence.

If speed simulation does occur then hearing speeded footsteps during sentence processing should affect comprehension of those sentences. Responses to sentences should be different when the speed of the sentence matches the speed of footsteps compared to when they do not match. Because there is no clear explanation in the literature for the difference between facilitation and interference effects (see section 2.4), I do not make a directional prediction in terms of an interaction.

6.1.1 Method

6.1.1.1 Participants

52[7] participants (35 females) took part in the experiment (mean age = 23.3, *SD* =4.9) for payment or course credit. One subject was removed for overall low accuracy (< 75%).

6.1.1.2 Material

Full-body speed verbs and speed adverbs were rated according to their speed by seven participants (age range 54-73, average 58.9). This age range was chosen because I intended to also use the present item set to assess comprehension in Parkinson's patients (Chapter 8), thus I needed ratings from healthy age-matched participants. Each rating session was divided into three sections: rating verbs for speed, rating adverbs for speed and rating verbs for valence. Valence values were used in the design of stimuli to be used in Chapter 8 (see section 8.1.2.3.). For speed ratings, participants were asked to rate how fast or slow the motion described by the word was on a scale of 1 to 7. A separate option of 'none' was available, placed outside of the speed scale. All verbs were preceded by 'to' so that only the verb meaning would be rated. For valence judgments participants were asked to rate how each word made them feel on 9-point scale of unhappy to happy (following the methodology used in Bradley & Lang, 1999). As a later consideration I decided to add verbs that described fast and slow hand/arm actions. Nine participants (age range 25-43, average 28.9) rated all potential words online using the same 7-point scale as used for the other verbs.

Verbs and adverbs were considered abstract if more than three participants had rated them as 'none' in terms of speed, all other verbs and adverbs were considered to be speed stimuli. However, abstract verbs were checked to ensure that their meaning

[7] The choice of number of participants was based on Kaschak et al. (2005) who used a similar paradigm (48 participants).

was abstract, according to my intuition. If a word's mean rating was greater than 3.5 it was considered 'fast' and if its mean rating was less than 3.5 it was considered 'slow'.

The lists of fast, slow and abstract full-body verbs (in past tense), fast, slow and abstract hand verbs (in past tense) and fast, slow and abstract adverbs that met the above criteria were submitted to a matching program 'Match' (van Casteren & Davis, 2007) which matched 20 triplets of fast, slow and abstract adverbs, 13 triplets of fast full-body, slow full-body and abstract verbs and 11 triplets of fast hand/arm verbs, slow hand/arm verbs and abstract verbs on number of letters, log frequency HAL, number of orthographic neighbours, number of phonemes, number of syllables, lexical decision response time, lexical decision accuracy and naming response time (when this data was available) as taken from the English Lexicon Project. However, not all adverbs fitted appropriately into sentences and so only 13 triplets of adverbs were used. Full-body verbs and matching statistics are displayed in Table Appendix 1-6 and 1-7, hand/arm verbs and matching statistics are displayed in Table Appendix 1-8 and 1-9 and adverbs and matching statistics are displayed in Table Appendix 1-10 and 1-11.

The matched words were placed into four types of speed sentences. Each sentence type was analysed separately:

(1) 11 hand/arm speeded action sentences in which speed is encoded via the verb e.g. "*Amy* stroked *her chin as she tried to remember*" versus "*Sarah* smacked *her head when she started to forget*". I was unable to fit the matched fast and slow hand/arm verbs into the same sentence because their meanings were so different. Thus, speed was manipulated between items and each participant saw both the fast and slow version.

(2) 13 full-body speeded action sentences in which speed is encoded via the verb e.g. "*The professor* stormed/sneaked *down the corridor*"[8]. Participants saw either a fast or slow version of each sentence, counterbalanced across participants.

(3) 13 concrete action sentences in which speed is encoded with an adverb e.g. "*John* speedily/awkwardly *rolled up the sleeping bag*". Participants saw either a fast or slow version of each sentence, counterbalanced across participants.

(4) 13 abstract action sentences in which speed is encoded with an adverb e.g. "*Bob* speedily/awkwardly *thought over the business plan*". Participants saw either a fast or slow version of each sentence, counterbalanced across participants.

Each speed sentence (both sentences with and without adverbs) was matched with an abstract sentence (using an abstract verb or adverb matched in the above process) in sentence length and several psycholinguistic features of the verbs. In addition to the initial matching of verbs for sentence types 1 and 2, and adverbs for sentence types 3 and 4, as described above, for adverb sentences the verbs following each adverb were also matched across the three sentence types in number of letters, log frequency HAL, number of orthographic neighbours, number of phonemes, number of syllables, lexical decision response time, lexical decision accuracy and naming response time (see Table Appendix 1-12 1-13). In addition 39 grammatically correct nonsense sentences that matched experimental sentences in length and syntactic structure were used e.g. *The frog installed the pan in the joy* (see Appendix section A2.1 for all sentences).

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[8] In comparison to hand/arm sentences, the actions described here are performed mainly with the legs but I will refer to them throughout the thesis as "full-body" rather than "leg" actions so that they are not confused with more stationary actions such as kicking.

The same adverbs were used with both concrete and abstract action sentences (sentence types 3 and 4), therefore each participant saw one adverb with a concrete action and its matched adverb with an abstract action. Figure 6-1 displays the distribution of sentence conditions for two participants.

The sound of fast and slow footsteps was taken from an online sound database (www.freesound.org). Both sets of footsteps sounded like a person walking or running on gravel. The slow condition played footsteps at a rate of 93 steps per minute and the fast condition played footsteps at a rate of 194 steps per minute.

6.1.1.3 Design & Analysis

Speed of footsteps and speed of sentence was a within subjects factor.

For hand action sentences, sentence speed (fast, slow or none (abstract)) was a between item manipulation, and all participants saw all sentences. For full-body sentences, participants viewed all abstract sentences but speed was a within item manipulation: participants viewed either a slow or fast version, counterbalanced across participants. Similarly, for adverb sentences, participants viewed all abstract sentences with abstract adverbs but viewed an abstract sentence with either a fast or slow adverb, and a concrete sentence with either a fast or slow adverb, counterbalanced across participants.

6.1.1.4 Procedure

The experiment was presented in E-Prime and participants were tested in a soundproof testing booth. Fast and slow footsteps were played via headphones on every trial (50% each), starting 3000ms before presentation of the sentence and finishing when a response was made or when the trial timed out (5000ms after sentence presentation). They saw the sentences presented on the computer screen and were asked to decide whether the sentence made sense or not by pressing ‘j’ on the keyboard for ‘yes’ and ‘f’ for ‘no’. Example nonsense sentences were given and it was emphasized that sensibility was based on meaning, not grammaticality. Participants were instructed to wear headphones and were informed in written instructions that they would hear the sound of footsteps during the task. Participants first completed six practice trials with feedback. Sentences were presented twice within the experiment, once with each speed of footsteps, to increase statistical power. The experiment was divided into two blocks and participants could choose to take a break midway. Each sentence was presented once in each block. Both accuracy and response time were recorded. The experiment lasted around 50 minutes.

Table 6-1. Example of the distribution of sentence conditions for two participants A and B.

A

Sentence Type	Abstract	Fast	Slow
Hand	*Ross scared the cat under the table*	*Rick shoved the bag behind the cupboard*	*Tom rolled the keg towards the doorway*
Full-body	*The brother mourned his recent loss*	*The professor stormed down the corridor*	
Adverbs-abstract	*Max usefully acquired all the new clients*		*Bob awkwardly thought over the business plan.*
Adverbs-concrete		*John speedily rolled up the sleeping bag.*	

B

Sentence Type	Abstract	Fast	Slow
Hand	*Ross scared the cat under the table*	*Rick shoved the bag behind the cupboard*	*Tom rolled the keg towards the doorway*
Full-body	*The brother mourned his recent loss*		*The professor sneaked down the corridor*
Adverbs-abstract	*Max usefully acquired all the new clients*	*Bob speedily thought over the business plan.*	
Adverbs-concrete			*John awkwardly rolled up the sleeping bag.*

6.1.2 Results

Items were removed from analysis if overall accuracy was less than 75%. This meant that for adverb-abstract sentences three items were removed and for full-body sentences one item was removed (an item including fast, slow and abstract version). Trials were removed if response time was outside 2.5 standard deviations of a subject's mean response times (< 4%).

Linear mixed effects models were used to analyse the data, with subjects and items as crossed random effects and sentence type and footsteps speed as fixed effects. Markov chain Monte Carlo approximation was used in all analyses to estimate p values. I first report a model including all three sentence types, with abstract sentences as the reference level (Model 1). I then report a model with abstract sentences removed, in order to compare fast and slow sentences types (Model 2).

The data was analysed overall as well as by Block 1 only, as sentences were presented twice, once with each speed of footsteps. All results from Experiment 6-1 are summarized in Table 6-1.

6.1.2.1 Hand Sentences

This section presents an analysis of response time and accuracy for sentences describing fast and slow actions specifically performed with the hands (e.g. *Rick shoved the bag behind the cupboard*). An interaction between sentence speed and footstep speed is predicted for fast and slow sentences.

6.1.2.1.1 Response time

For response time across both blocks, Model 1 revealed that responses to abstract sentences were slower than responses to fast (β = -.1, t = 2.03, p = .04) and slow sentences (β = -.11, t = 2.17, p = .03). This effect is in line with the typical concreteness effect in which concrete language is processed faster and more accurately than abstract language (Paivio, 1971, 1986, 2007; Schwanenflugel & Shoben, 1983). There was no effect of footsteps (t <1) and no significant interaction when comparing abstract and slow sentences across footsteps (t <1) or when comparing abstract and fast sentences across footsteps (β = .02, t =1.1, p = .27). For Model 2, there was no difference between fast and slow sentences, no difference between fast and slow footsteps, and no interaction between the two (all ts < 1)

When looking at block l only, Model 1 found responses to abstract sentences were marginally slower than responses to fast sentences (β = -.12, t = 1.76, p = .08) and statistically slower than responses to slow sentences (β = -.15, t = 2.3, p = .02). Neither the interactions nor the effect of footstep speed were significant (ts < 1). For Model 2, there was no difference between fast and slow sentences, no difference between fast and slow footsteps, and no interaction between the two (all ts < 1)

In terms of the present hypothesis, no effects of an interaction between footstep speed and sentence speed were observed in response time measures. LME predicted mean response times are displayed in Figure 6-1.

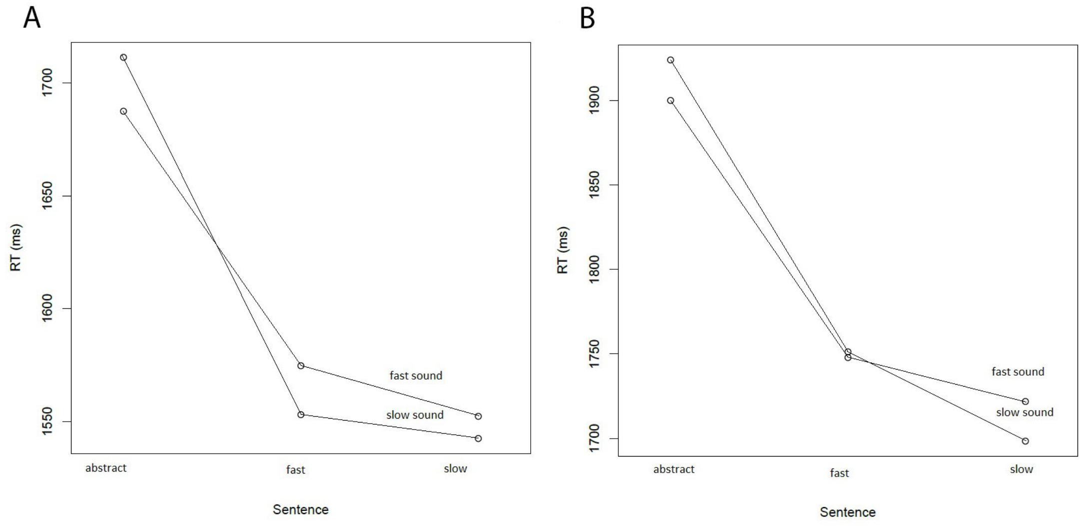

Figure 6-1. LME predicted response time for hand sentences in Experiment 6-1, both blocks (A) and Block 1 only (B).

6.1.2.1.2 Accuracy

Across both blocks, Model 1 found that accuracy for abstract sentences was significantly lower than fast sentences (β = .7, z = 3.17, p < .01) and marginally lower than slow sentences (β = .46, z = 1.72, p = .09). There was no effect of footsteps (z < 1) and no significant interaction when comparing abstract and fast sentences across footsteps (β = -.18, z = 1.57, p = .11) or when comparing abstract and slow sentences across footsteps (z < 1). For Model 2, there was no difference between fast and slow sentences (β = -.26, z = 1.49, p = .14), no difference between fast and slow footsteps (β = -.09, z = 1.43, p = .15), and no interaction between the two (β = .2, z = 1.56, p = .12).

When looking at block 1 only, Model 1 again found that accuracy was lower for fast sentences than abstract sentences (β = .66, z = 2.76, p < .001), but there was no difference between slow and abstract sentences (β = .54, z = 1. 31, p = .19). There was no effect of footsteps (z <1) and no significant interaction when comparing abstract and fast sentences across footsteps (β = -.21, z = 1.38, p = .17) or when comparing abstract and slow sentences across footsteps (β = .17, z = 1.2, p = .23). For Model 2, there was no difference between fast and slow sentences (β = -.16, z = 1.48, p = .14), no difference between fast and slow footsteps (β = -.04, z = 1.54, p = .23), but there was a significant interaction between the sentence speed and footsteps speed (β = .38, z = 2.16, p = .03). The interaction shows that responses were more accurate when footsteps speed and sentence speed matched compared to when they didn't match. However, the interaction does not quite meet a Bonferonni-corrected alpha level of .025 (required as looking at Block 1 only was a post-hoc comparison).

Across all analyses for sentences describing hand actions responses to abstract sentences were less accurate than responses to fast and slow sentences, reflecting the "concreteness effect". Critically, in line with my hypothesis I found a marginally significant interaction between sentence speed and footstep speed such that responses were more accurate when the two speeds matched (in block 1 only), reflecting a facilitation effect with matching speed. LME predicted mean accuracy is displayed in Figure 6-2.

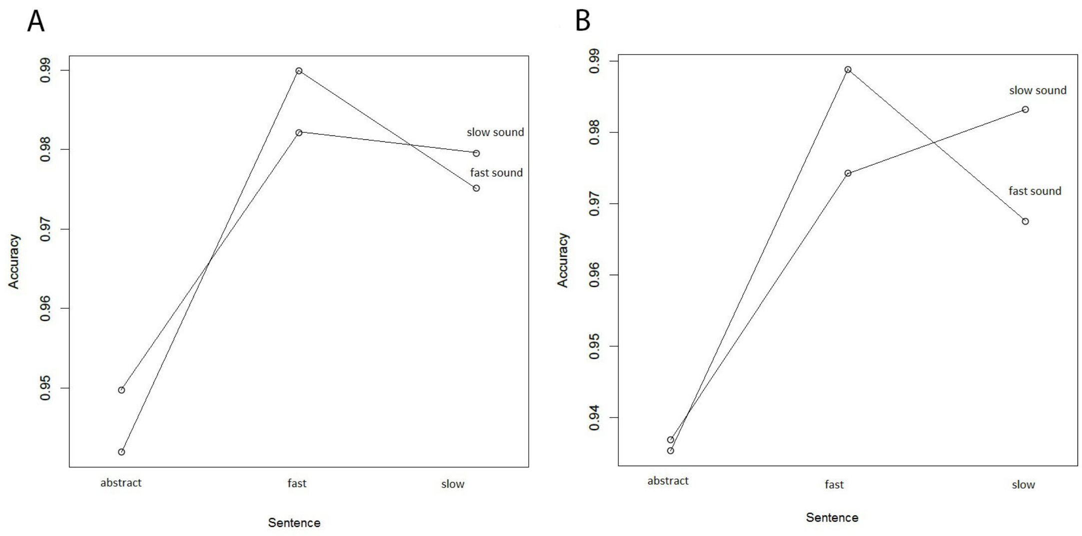

Figure 6-2. LME predicted accuracy for hand sentences Experiment 6-1, both blocks (A) and Block 1 only (B).

6.1.2.2 Full body sentences

This section presents an analysis of response time and accuracy for sentences describing fast and slow actions specifically performed with the whole body (e.g. *The professor stormed down the corridor*). An interaction between sentence speed and footstep speed is predicted.

6.1.2.2.1 Response time

For response time across both blocks, Model 1 revealed that there was no difference between abstract sentences and fast or slow sentences (*t*s < 1). There was no interaction when comparing abstract and slow sentences across footsteps (β = -.02, *t* =1.4, *p* = .16) or when comparing abstract and fast sentences across footsteps (*t* < 1). There was however, a significant effect of footsteps speed (β = .04, *t* = 2.26, *p* = .02). For Model 2, there was no difference between fast and slow sentences, no difference between fast and slow footsteps, and no interaction between the two (all *t*s < 1)

When looking at block 1 only, again Model 1 found no difference in responses between abstract and fast sentences (β = -.05, t = 1.28, p = .2) or abstract and slow sentences (β = -.06, t = 1.16, p = .25). There was no interaction when comparing abstract and slow sentences across footsteps (β = -.02, t = 1.13, p = .26) or when comparing abstract and fast sentences across footsteps (t < 1) and there was no effect of footsteps speed (t = 1.36, p = .17). For Model 2, there was no difference between fast and slow sentences (t < 1), no difference between fast and slow footsteps (β = -.01, t = 1.11, p = .27), and no interaction between the two (β = t =1.03, p = .3)

In terms of the present hypothesis, no effects of an interaction between footstep speed and sentence speed were observed in response time measures. LME predicted mean response times are displayed in Figure 6-3.

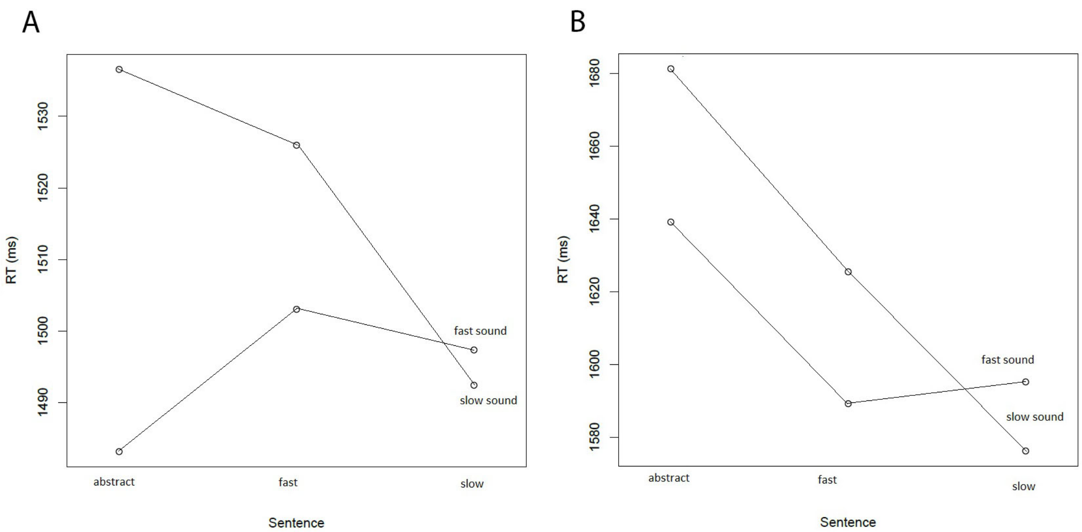

Figure 6-3. LME predicted response time for full body sentences in Experiment 6-1, both blocks (A) and Block 1 only (B).

6.1.2.2.2 Accuracy

Across both blocks, Model 1 found that accuracy for abstract sentences was significantly higher than fast sentences (β = -.48, z = 4.12, p < .001) but not slow sentences ($z = 1.3$, $p = .19$). There was no effect of footsteps ($z < 1$) and no significant interaction when comparing abstract and fast sentences across footsteps ($z < 1$) or when comparing abstract and slow sentences across footsteps ($z < 1$). For Model 2, responses were less accurate for fast sentences than slow sentences ($\beta = .22$, $z = 2.6$, $p < .01$), there was a marginal effect of footstep speed ($\beta = .07$, $z = 1.81$, $p = .07$) and there was a marginal interaction between sentence type and footstep speed ($\beta = .24$, $z = 1.9$, $p = .06$).

When looking at block 1 only, Model 1 found no difference in accuracy between fast sentences and abstract sentences ($\beta = -.25$, $z = 1.68$, $p = .09$) or between slow and abstract sentences ($\beta = -.1$, $z = 1.04$, $p = .3$). There was no effect of footsteps ($\beta = .46$, $z = 1.63$, p = .1) and no significant interaction when comparing abstract and fast sentences across footsteps ($z < 1$) or when comparing abstract and slow sentences across footsteps ($\beta = -.39$, $z = 2$, $p = .05$), using a Bonferonni-corrected alpha of .025, for multiple comparisons (looking at Block 1 only is a post-hoc analysis). For Model 2, there was a marginally significant difference between fast and slow sentences according to the adjusted alpha level ($\beta = .22$, $z = 2.23$, $p = .03$), with accuracy lower for fast sentences than slow sentences. There was also a marginally significant interaction between sentence type and footstep speed ($\beta = -.47$, $z = 2.22$, $p = .03$), with sentences less accurate when speed of footsteps matched speed of sentence, than when they did not match. There was no effect of footstep speed ($\beta = .04$, $z = 1.82$, $p = .07$).

LME predicted mean accuracy is displayed in Figure 6-4.

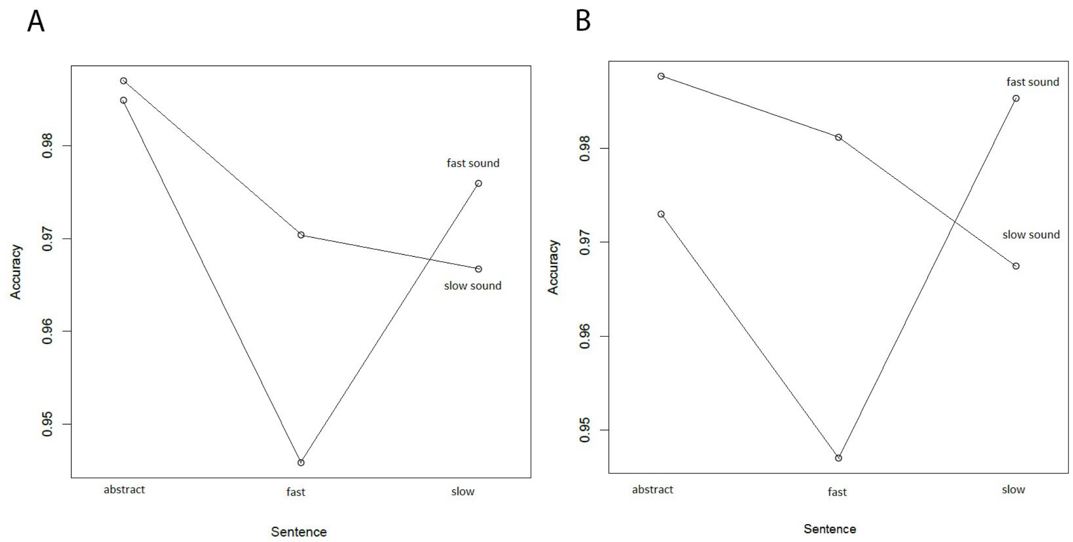

Figure 6-4. LME predicted accuracy for full body sentences Experiment 6-1, both blocks (A) and Block 1 only (B).

6.1.2.3 Adverb sentences with abstract actions

This section presents an analysis of response time and accuracy for sentences describing abstract actions that are modified by adverbs (e.g. *Bob speedily thought over the business plan.*). By combining speeded adverbs with abstract actions I can test whether speed simulation can also be observed for actions that are not concrete. If speed is simulated then an interaction between sentence speed and footstep speed is predicted.

6.1.2.3.1 Response time

For response time across both blocks, Model 1 revealed that responses to abstract sentences were faster than fast (β = .04, t = 2.28, p = .02) and slow sentences (β = .04, t = 2.07, p = .03). There was no interaction when comparing abstract and slow sentences across footsteps or when comparing abstract and fast sentences across footsteps (*t*s < 1). There was however, a significant effect of footsteps speed (β = .05, t = 2.43, p = .01). For Model 2, there was no difference between fast and slow sentences, no difference between fast and slow footsteps, and no interaction between the two (all *t*s < 1)

When looking at block 1 only, Model 1 found no difference in responses between abstract and fast sentences (β = .03, t = 1.25, p = .21) or abstract and slow sentences (β = .04, t = 1.16, p = .25). There was no interaction when comparing abstract and slow sentences across footsteps or when comparing abstract and fast sentences across footsteps (*t*s < 1) and there was no effect of footsteps speed (t < 1). For Model 2, there was no difference between fast and slow sentences, no difference between fast and slow footsteps and no interaction between the two (t < 1)

In terms of the present hypothesis, no effects of an interaction between footstep speed and sentence speed were found. LME predicted mean response times are displayed in Figure 6-5.

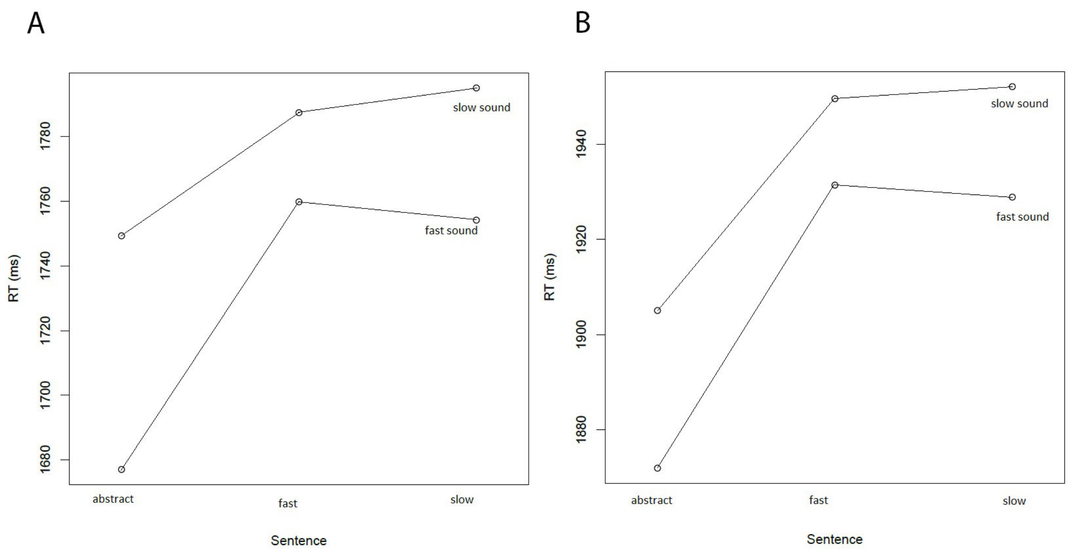

Figure 6-5. LME predicted response time for abstract adverb sentences in Experiment 6-1, both blocks (A) and Block 1 only (B).

6.1.2.3.2 Accuracy

Across both blocks, Model 1 found that accuracy for abstract sentences was significantly higher than slow sentences (β = -3, z = 3.18, $p < .001$) but not fast sentences ($z < 1$). There was no effect of footsteps ($z < 1$) and no significant interaction when comparing abstract and fast sentences across footsteps ($z < 1$) or when comparing abstract and slow sentences across footsteps (β = .18, z = 1.52, p = .13). For Model 2, responses were less accurate for slow sentences than fast sentences (β = -38, z = 3.06, $p < .01$), there was no effect of footstep speed ($z < 1$) and no interaction between sentence type and footstep speed (β = .26, z = 1.6, p = .11).

When looking at block 1 only, Model 1 found that accuracy was lower for slow sentences than abstract sentences (β = -.33, z = 2.69, $p < .01$), but there was no difference between fast and abstract sentences ($z < 1$). There was no effect of footsteps (β = -.04, z = 1.63, p = .1) and no significant interaction when comparing abstract and fast sentences across footsteps ($z < 1$) or when comparing abstract and slow sentences across footsteps (β = .22, z = 1.37, p = .17). For Model 2, there was a significant difference between fast and slow sentences (β = -.47, z = 2.25, p = .02), with accuracy lower for slow sentences than fast sentences (Bonferonni-corrected alpha of .025). There was no interaction between sentence type and footstep speed and no effect of footstep speed (zs < 1).

LME predicted mean accuracy is displayed in Figure 6-6.

A B

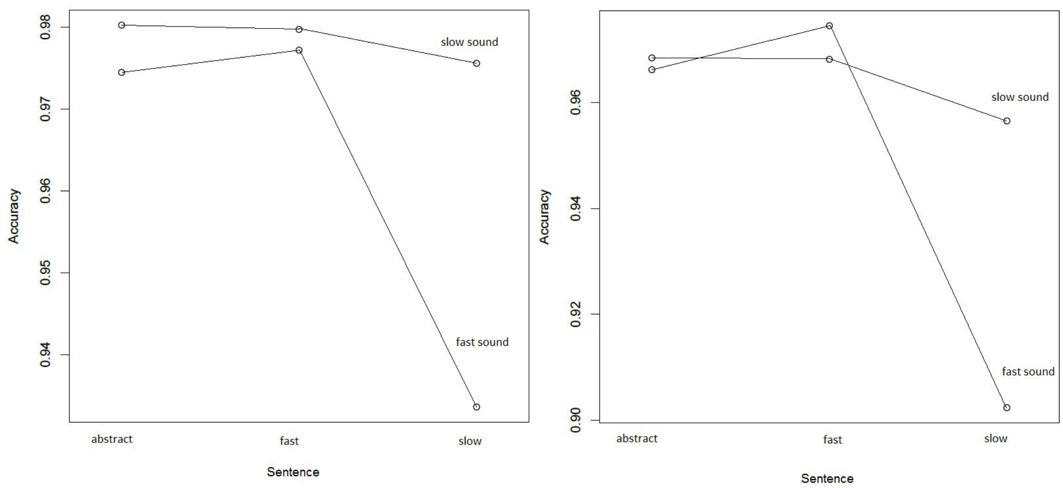

Figure 6-6. LME predicted accuracy for abstract adverbs sentences Experiment 6-1, both blocks (A) and Block 1 only (B).

6.1.2.4 Adverb sentences with concrete actions

This section presents an analysis of response time and accuracy for sentences describing concrete actions that are modified by adverbs (e.g. *John speedily rolled up the sleeping bag.*). An interaction between sentence speed and footstep speed is predicted.

6.1.2.4.1 Response time

For response time across both blocks, there was no difference between fast and slow sentences (β = .05, t = 1.52, p = .13), no difference between fast and slow footsteps, and no interaction between the two (t<1)

When looking at block 1 only, there was no difference between fast and slow sentences (β = .05, t = 1.53, p = .13), no difference between fast and slow footsteps and no interaction between the two (t < 1)

Thus there was no support for the predicted interaction between footstep speed and sentence speed in response time measures.

LME predicted mean response times are displayed in Figure 6-7.

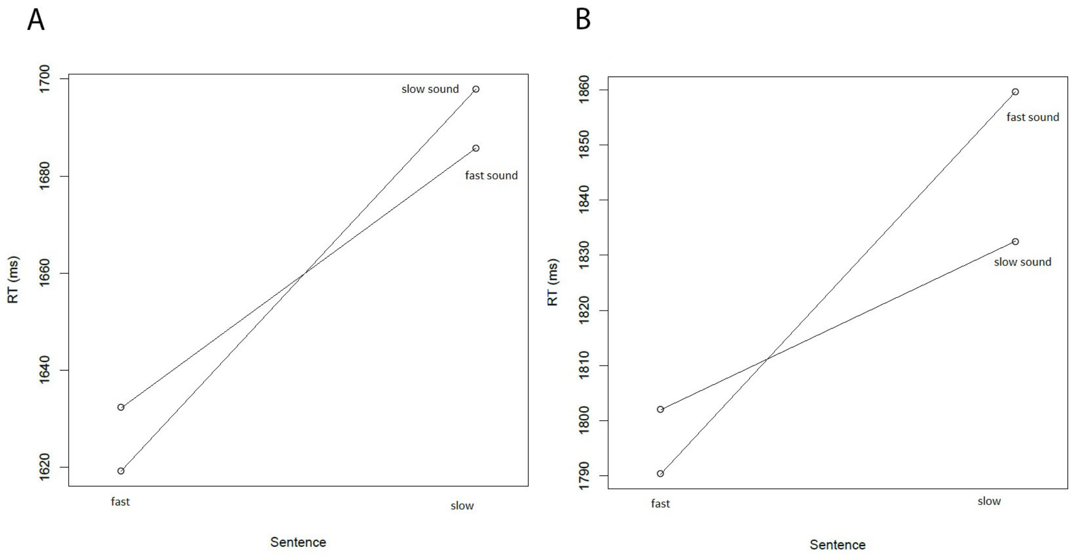

Figure 6-7. LME predicted response time for concrete adverb sentences in Experiment 6-1, both blocks (A) and Block 1 only (B).

6.1.2.4.2 Accuracy

When looking at both blocks together there was a marginally significant interaction between footstep speed and sentence speed (β = .28, z = 1.89, p = .06). Accuracy was higher when sentence speed matched speed of footsteps. There was no effect of footsteps (β = -.03, z = 1.41, p = .16) and no effect of sentence speed (β = -.09, z = 1.72, p = .09)

For accuracy by block 1 only, there was no effect of footsteps (β = -.16, z = 1.25, p = .21) no effect of sentence type (β = -.22, z = 1.46, p= .15) and no interaction (β = .31, z = 1.3, p = .2).

LME predicted mean accuracy is displayed in Figure 6-8.

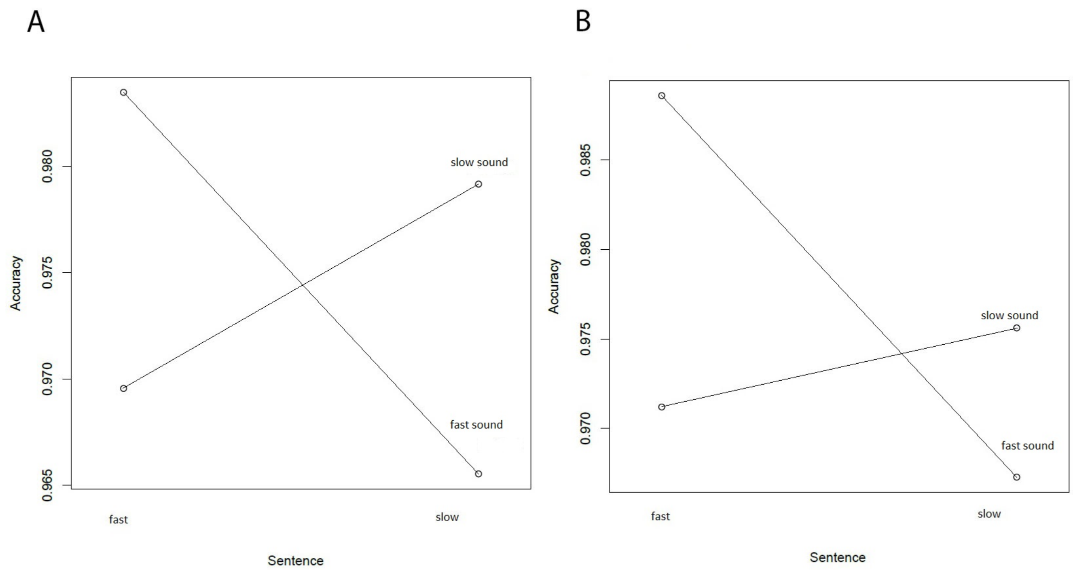

Figure 6-8. LME predicted accuracy for concrete adverbs sentences Experiment 6-1, both blocks (A) and Block 1 only (B).

6.1.3 Discussion

There was an effect of footsteps speed in two sentence conditions (full body sentences and adverbs with abstract actions sentences) in which responses were slower with slow footsteps. This suggests that the slow footsteps actually prime slower movements.

For both the hand and full body sentence sets, response time was longer for abstract sentences compared to fast and slow sentences. This is evidence of the concreteness effect (see Chapter 1 for discussion), often observed in the literature (Paivio, 1971; 1986; 2007; Schwanenflugel & Shoben, 1983).

The central findings of the experiment however are that the predicted interaction between footstep speed and sentence speed was observed across sentences describing hand actions, full body action, and concrete actions with adverbs, in accuracy measures. The interactions however, *just* fell short of statistical significance. The direction and timing of the marginally significant interactions (in terms of whether the effect was observed across both blocks or in the first block only) differed between sentence sets. For hand sentences, an interaction was observed in block 1 only. This interaction reflected more accurate responses for matching speed conditions compared to non-matching speed conditions. This facilitation effect suggests that sentence processing and auditory processing share a common resource in terms of speed and that preactivation of this resource by sounds leads to greater comprehension of sentences matching in speed. That the effect was only observed in block 1 suggests that comprehension is shallow in the second block of the experiment where the same sentences are presented again because participants easily recognize the sentence and their previous response and do not have to fully comprehend the sentence. An interaction in accuracy scores was also observed for full-body sentences in block 1 only. However, the direction of effect differed to that for hand sentences in that responses were *less* accurate when the speed of a sentence matched the speed of footsteps. This again implies shared resources between sentence speed and auditory speed, but now that preactivation of this resource interferes with comprehension of sentences. For adverb sentences with concrete actions, interaction effects were found in the experiment overall but not at block 1 only. One interpretation for this could be that effects with speed adverbs are weaker than with speed verbs and so more power is needed. Alternatively, speed effects with adverbs may take a longer time to develop than with speed verbs. For adverb sentences with both concrete and abstract actions the pattern of accuracy was similar to that for hand sentences, with accuracy higher for matching conditions (although only with slow sentences for adverb sentences with abstract actions). Thus, across two sentence types there was a facilitation effect in accuracy, whereas in one sentence type there is an interference effect in accuracy. Why would the direction of effect be different for full body sentences?

Although the sound of footsteps were used to reflect auditory speed relevant to human action, the sounds themselves specifically reflect full-body actions (i.e. running and walking) and not hand actions. Thus, they match the full-body sentences in terms of specific action features (using the legs/feet) but do not match the other sentences in this way. Note that the action verbs used in the adverb sentences with concrete actions were primarily actions performed with the hand/arms (e.g. *press*, *pull*, *grasp*) and thus could also be considered ‘hand sentences’. The difference in direction of the interaction in accuracy could therefore be explained by the degree of match between the auditory stimulus and the actions described in the sentence (similar to the results of Chapter 4). When there is a match in both speed and action type (e.g. fast footsteps and fast full-body action sentences), there is a complete overlap in processing and the system is fully saturated. There are therefore little resources available to process the sentence. Conversely, when there is only a match in speed and not in action type (e.g. fast footsteps and fast hand action sentences) there is only partial overlap in processing. This partial activation will then act as a boost in the processing of the sentence (a “head start”).

Effects are only found in accuracy measures however most embodied findings typically find effects in response time (e.g. Stanfield & Zwaan, 2001; Zwaan et al., 2002; Zwaan et al., 2004). One could argue that effects in accuracy suggest a stronger effect than an effect in response time: rather than simply interfering and slowing down processing, participants actually make mistakes. It seems more problematic to make more mistakes than to simply get to the correct answer more slowly. In Chapter 4 I found an effect of footsteps on response time in a lexical decision task. However, a sentence sensibility task may be more difficult than the lexical decision task. Due to the prevalent use of metaphor in language, many of the nonsense sentences may not so obviously be “nonsense”. The increased difficulty of the task may have made accuracy measures more sensitive. Thus it is possible that interaction effects in accuracy would be observed for the lexical decision task in

Chapter 4 if it were a more difficult task. However, the non-words were designed to be very word-like so it is not clear how it could be made more difficult.

As a manipulation check I observed effects of footstep speed in response time, showing that participants sufficiently processed the sounds. Further, I have demonstrated the typical concreteness effect. Across three sentence sets I have observed a marginal interaction between sentence speed and footsteps speed in accuracy scores, however the direction of this effect appears to be dependent on specific action features of the sentence and auditory stimulus. It should be emphasized however, that the results do not meet a Bonferonni-corrected alpha level (because the Block 1 analyses were post-hoc). Thus, the interaction effects should be replicated again in another experiment, in which effects in only Block 1 are predicted. Table 6-2 summarizes the main findings of Experiment 6-1.

Experiment 6-1 suggests that auditory speed is simulated during sentence comprehension. The chapter now moves toward another domain in which speed simulation may be observed: action.

Table 6-2 Summary of results Experiment 6-1. A single tick mark indicates a significant effect in response time and a tick mark within a box indicates a significant effect in accuracy. Only effects with p-values< 0.05 are included.

Hand sentences

	All blocks		**Block 1**	
	Model 1	**Model 2**	**Model 1**	**Model 2**
Footstep Speed				
Sentence Type				
Abstract vs. Fast	✓ ☑		☑	
Abstract vs. Slow	✓		✓	
Fast vs. Slow				
Footsteps * Sentence Type				

Abstract vs. Fast				
Abstract vs. Slow				
Fast vs. Slow				

Full-body sentences

	All blocks		Block 1	
	Model 1	**Model 2**	**Model 1**	**Model 2**
Footstep Speed	✓			
Sentence Type				
Abstract vs. Fast	☑			
Abstract vs. Slow				
Fast vs. Slow		☑		
Footsteps * Sentence Type				
Abstract vs. Fast				
Abstract vs. Slow				
Fast vs. Slow				

Adverb sentences (abstract)

	All blocks		Block 1	
	Model 1	**Model 2**	**Model 1**	**Model 2**
Footstep Speed	✓			
Sentence Type				
Abstract vs. Fast	✓			
Abstract vs. Slow	✓ ☑		☑	
Fast vs. Slow		☑		☑

Footsteps * Sentence Type *Abstract vs. Fast* *Abstract vs. Slow* *Fast vs. Slow*				

Adverb sentences (concrete)

	All Blocks	**Block 1**
	Model 1	**Model 2**
Footstep Speed		
Sentence Type *Fast vs. Slow*		
Footsteps * Sentence Type *Fast vs. Slow*		

6.2 Experiment 6-2: Manipulating Speed of Physical Action

So far this thesis has addressed the perceptual simulation of speed. As described in the literature review (Chapter 2) there have also been many studies showing motoric simulation for action language (e.g. Rueschemeyer et al., 2010; Buccino et al., 2005; Boulenger et al., 2009; Hauk et al., 2004). That is, when understanding action words, parts of the motor and premotor cortex (systems involved in planning and executing actions) are recruited. The meaning of words and sentences about speed of actions is likely to include both perceptual information of different modalities (see Chapter 4) and motoric information. To simulate the meaning of a word like *run* one may simulate the perceptual experience of watching another person running, as well as the motoric experience of planning and executing a run with one's own body (as well as associated perceptual experiences). Results so far within the literature show that action simulations include specific information such as direction of action (Glenberg

& Kaschak, 2002) and effector used in the action (Hauk et al., 2004), but what about more fine-grained parameters of action? It is unclear to what extent action simulations mirror real-world action. For example, action simulations may include coarse action representations, coding for salient features such as effector and direction, but they may not contain fine-grained temporal and spatial features that real-world actions require for precision. By addressing the motoric simulation of speed in sentences I expand on previous research and further explore the action simulations that arise during comprehension of action sentences. I do this by using the same sentences from Experiment 1 and assessing the effect of speeded actions on their comprehension. If action simulations are sensitive to parameters that are vital for accurate real-world motor behaviours, then I expect that speed of action is coded in simulations.

Participants' speed of movement was covertly manipulated by attaching wraps with or without weights to their arms and legs. They then completed a movement task in order to experience moving at a normal versus slowed pace. Participants then completed the same sentence sensibility task as in Experiment 6-1. The procedure for this experiment differs from Experiment 6-1 due to constraints involved with manipulating speed of physical movement. Manipulating speed of action during sentence processing may lead to unwanted attentional demands and further, forcing participants' actions to be fast or slow may interfere with measurements of comprehension (reaction time), washing out any effect of the interaction between sentence speed and action speed For instance, if participants are moving fast due to the action manipulation it may be difficult to detect whether responses to the language stimuli are facilitated. Thus, I decided to manipulate action speed before presenting participants with the sentence task. Elsewhere studies have shown that sufficient motor experience before a language task can lead to changes in processing of action language. According to the Body Specificity hypothesis (Casasanto, 2009), any changes in body experience should subsequently lead to changes in the way that language about the body is understood. For example, reading words referring to actions typically performed with the dominant hand led to different motor activity between right and left-handers (Willems et al., 2010). Similarly, Beilock et al. (2008) found that long-term experience of playing hockey led to faster comprehension of hockey language compared to novices. Further, it has been shown that experimentally induced motor experience can affect action language comprehension. Locatelli, Gatti and Tettamanti (2012) trained participants on a number of fine hand movements over a three week period and found performance on a sentence-picture matching task for sentences about similar hand actions to be significantly faster after training than before training. In fact, training the motor system for only 20 minutes can induce comprehension effects: Glenberg et al. (2008) had participants move 600 beans from one container to another with a movement either towards or away from the body. After this short duration the motor system had adapted to a particular direction and on a subsequent language task, responses were facilitated for sentences describing movement in a matching direction.

Here I used a motor task in which participants moved cans to specified locations on a table a fixed number of times. I covertly manipulated the speed of movement of the participants by instructing them to wear arm and ankle wraps that either contained weights or were empty. Wearing weights in the wraps leads to slow arm and leg movements and makes movement more difficult. After completing the motor task, participants sat down to complete the sentence sensibility task. In order to keep the link between the motor task and the sentence task hidden I created a cover story for both tasks. By hiding the weights within the wraps and attaching non-functional electrodes to each participant's legs and arms, I set up a false skin conductance recording device and informed participants that they would participate in a task assessing changes in skin conductance whilst producing large (can movements) and small (keyboard presses and eye movements in a sentence reading task) movements. If wearing weights sufficiently leads to slower movements then I predict that comprehension of sentences describing slow movements will be quicker than sentences describing fast movements, because the motor system will be in a matching state of speed. The converse is predicted when no weights are worn: responses will be faster for fast sentences than slow sentences. In sum, an interaction is predicted between weights (present or absent) and sentence type (fast or slow). Since the weights are attached to the arms and the ankles, I predict the same pattern in full-body sentences and hand sentences. If abstract actions are grounded in concrete actions then I predict the same pattern for adverb sentences with concrete and abstract actions.

6.2.1 Method

6.2.1.1 Participants

59[9] participants took part (44 female, average age 21.25, *SD* = 2.71). All participants were psychology students from the University of South Carolina, taking part for course credit. Three participants were removed for having overall accuracy less than 75%, one participant was removed because they were dyslexic and two participants were removed for indicating scepticism about the skin conductance measurement.

6.2.1.2 Material

The same set of sentences was used as in Experiment 6-1

6.2.1.3 Design

Participants either wore arms and ankle wraps with weights (three pounds (0.9kg) on each wrist and five pounds (2.3kg) on each ankle) or arm and ankle wraps without weights, manipulated between subjects (28 with weights, 31 without weights).

The experiment used the same sentences as Experiment 6-1, but each sentence was presented only once.

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[9] Since weights was a between subjects condition, the number of participants needed to be larger than Experiment 6-1. Thus the study may be underpowered. Note that testing was still taking place in South Carolina during thesis submission.

6.2.1.4 Procedure

6.2.1.4.1 Cover story

In order to manipulate the weight worn by the subjects, I came up with a cover story for why they had to wear wraps, in order to hide the true aims of the study. Upon arrival at the experiment participants were told that they were participating in a study that investigates how skin conductance changes with small and large movements. Skin conductance would be measured whilst they completed a task in which they moved cans around a table (large arm movements) and whilst they completed a reading task on the computer (small hand movements and eye movements). They were told that wearing the wrist wraps increases the skin conductance recording, so that the signal would be maximized.

After filling out the consent forms, four fake recording devices were fitted to each participant along with wraps that either contained weights or did not. Electrodes were attached to the forearms and calves of each participant and simulated a recording system. Wraps were placed around each subject's wrist and ankles. For the weights condition, there were three weights in each arm wrap and five weights in each ankle wrap, with each weight weighing one pound. In order to make the cover story more believable, two experimenters acted out a process of checking an electrode's signal and subsequently altering its position.

6.2.1.4.2 Movement task

Participants were stood at one end of a table in front of an arrangement of five full tin cans. They were instructed to move the cans, one at a time, using alternate hands, to the other end of the table and place them in the same arrangement as indicated by stickers on the table. The length of the table was long enough so that participants had to move their legs as well as their arms to complete the task. At the point in which a can was put in the correct location, the participant's body also had to be in an indicated location so that they would actually move their body, rather than simply stretch to complete the task. When all cans were placed at the other end of the table, participants had to move them back to the original position in the same manner. Participants had to complete this full cycle eight times. The time taken to complete the task was recorded covertly by an experimenter.

The set-up of the movement task is displayed in Figure 6-9.

6.2.1.4.3 Sentence sensibility task

Participants were seated in front of a laptop after completing the movement task and the electrodes were checked again. They were again told that the purpose of this task was to make small movements with the hands and eyes. It was explained that eye-movements were not being recorded but that we were measuring accuracy on the task to check that they were actually reading the sentences.

The sentence sensibility task was then completed in the same way as Experiment 6-1 except that now each sentence was presented only once.

6.2.1.4.4 Debriefing

After completing the sentence task the true aims of the experiment were explained to the participants and they signed a debrief form. They were also asked if they had realized the true purpose of the experiment at any points (two participants were sceptical and were removed from analysis).

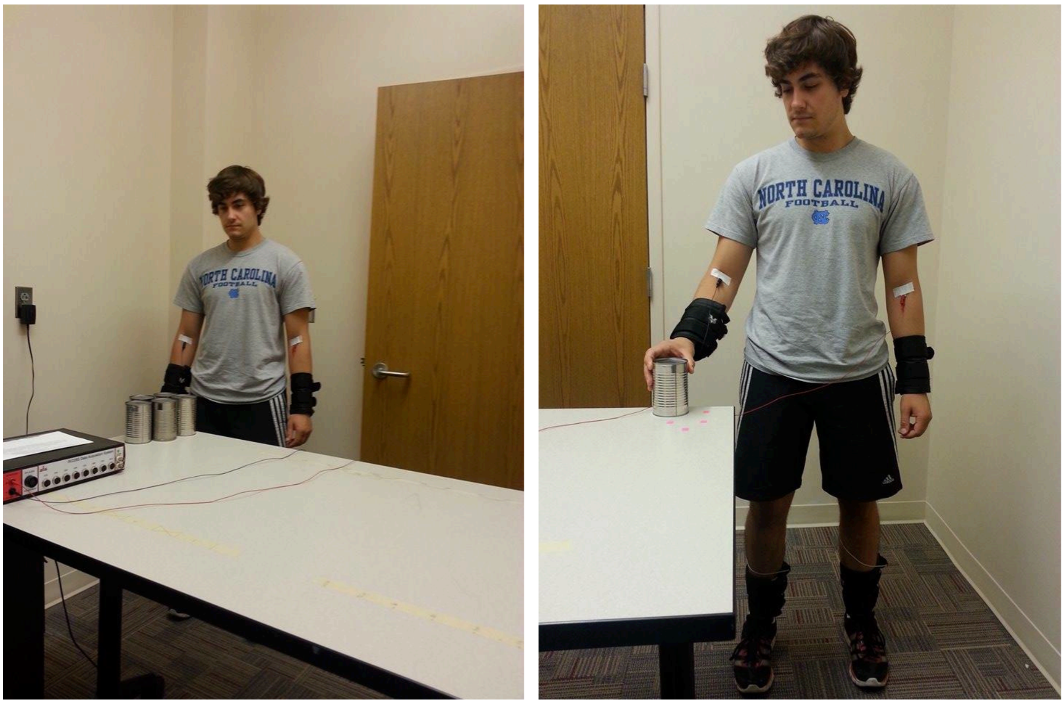

Figure 6-9. Movement task in Experiment 6-2. Participants wore arm and leg wraps that did or did not contain weights and had fake electrodes attached to their arms and legs that were hooked up to a pretend recording device.

6.2.2 Results

Items were removed from analysis if overall accuracy was less than 75%. This meant that for adverb-abstract sentences five items were removed, for full-body sentences six items was removed and for hand sentences one item was removed (an item including fast, slow and abstract version).

Trials were removed if response time was outside 2.5 standard deviations of a subject's mean response times (< 2%).

6.2.2.1 Movement times

As a manipulation check, I measured how long it took each participant to complete the movement task and compared the mean time for participants wearing weights to those not wearing weights (although movement time for one participant in the weights condition and one participant in the no weights condition were not recorded due to experimenter error). Independent t-tests found that there was a significant difference in movement times (t (50) = 1.77, p = .041, d = .49, one-tailed) with participants wearing weights taking longer than those without weights with a mean difference of 55.44 seconds (Figure 6-10). Therefore, the weights manipulation was successful: wearing weights slowed down movement speed compared to participants not wearing weights.

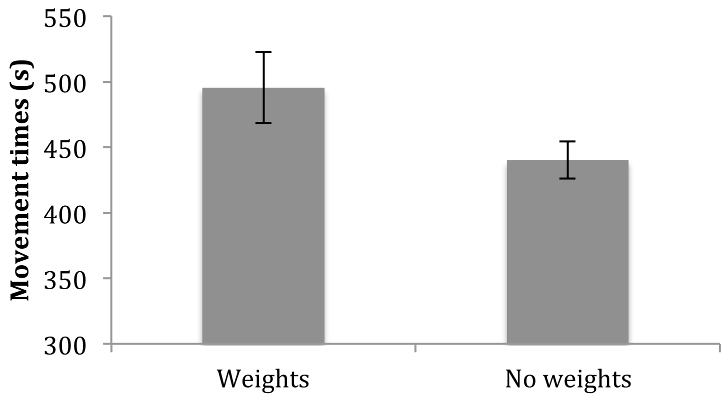

Figure 6-10. Average time to complete movement task for weights and no weights conditions in Experiment 6-2. Error bars reflect 1 standard error.

6.2.2.2 Hand sentences

This section presents an analysis of response time and accuracy for sentences describing fast and slow actions specifically performed with the hands (e.g. *Rick shoved the bag behind the cupboard*). An interaction between sentence speed and weights condition is predicted.

6.2.2.2.1 Response time

Model 1 revealed that responses to abstract sentences were marginally slower than fast (β = -.21, t = 1.73, p = .08) and slow sentences (β = -.23, t = 1.87, p = .06). There was no interaction when comparing abstract and slow sentences across footsteps or when comparing abstract and fast sentences across footsteps (*t*s < 1), and no effect of weights (β = -.12, t = 1.64, p = .1). For Model 2, there was no difference between fast and slow sentences and no interaction between the two (t <1). There was however a significant effect of weights with responses faster with weights than without (β = -.14, t = 1.95, p = .05).

Thus there was no evidence for the predicted interaction between weights condition and sentence speed in terms of response time. LME predicted mean response times are displayed in Figure 6-11.

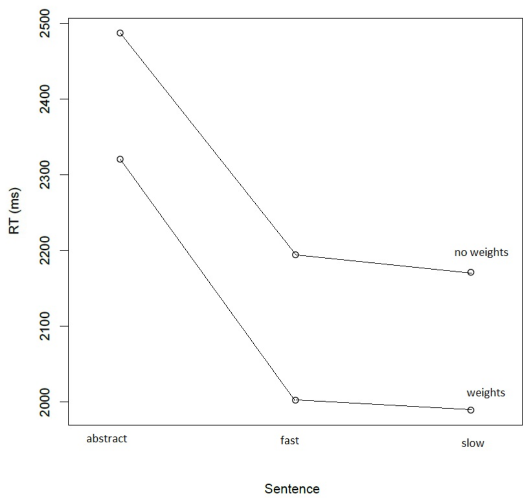

Figure 6-11. LME predicted response time for hand sentences in Experiment 6-2.

6.2.2.2.2 Accuracy

In Model 1, there was no difference in accuracy between abstract sentences and fast (β = .88, z = 1, p = .31) or slow sentences (z < 1), and there was no effect of weights (z < 1). The interaction of sentence type and weights condition was significant comparing only fast and abstract sentences (β = .54, z = 2.36, p = .02) and marginally significant comparing slow and abstract sentences (β = .29, z = 1.74, p = .08). Since both interactions were in the same direction, I decided to collapse across fast and slow sentences and run the model again comparing abstract sentences with ''speed'' sentences. This revealed a significant interaction ($\beta = .37$, $z = 2.67$, $p < .01$) such that responses to speed words were more accurate when wearing weights compared to not wearing weights, but the opposite pattern was observed with abstract sentences. For Model 2, there was no difference between fast and slow sentences and no interaction ($z < 1$), but there was a main effect of weights, with accuracy higher when wearing weights compared to not wearing weights, reflecting the above interaction.

Thus, the main prediction of an interaction between weights condition and sentence speed was partially supported in that responses were different between abstract sentences and speed sentences between weights conditions. This may reflect an effect of action in general rather than speed.

LME predicted mean accuracy is displayed in Figure 6-12.

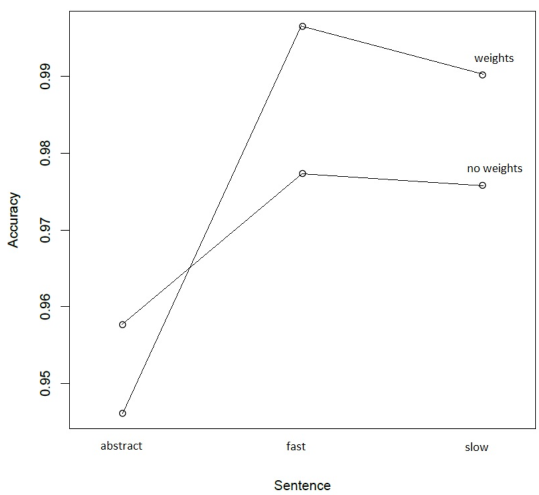

Figure 6-12. LME predicted accuracy for hand sentences Experiment 6-2.

6.2.2.3 Full body sentences

This section presents an analysis of response time and accuracy for sentences describing fast and slow actions specifically performed with the whole body (e.g. *The professor stormed down the corridor*). An interaction between sentence speed and weights condition is predicted.

6.2.2.3.1 Response time

Model 1 revealed that responses to abstract sentences were slower than fast (β = -.1, t = 2.45, p = .02) and slow sentences (β = -.09, t =2.38, p = .02). There was no interaction when comparing abstract and slow sentences across footsteps or when comparing abstract and fast sentences across footsteps (ts<1), and no effect of weights (β =, t = 1.82, p = .07). For Model 2, there was no difference between fast and slow sentences, no interaction between the two (t <1) and no effect of weights (β = -.1, t = 1.39, p = .17).

Thus, there was no support for the predicted interaction between weights condition and sentences speed in response time. LME predicted mean response times are displayed in Figure 6-13.

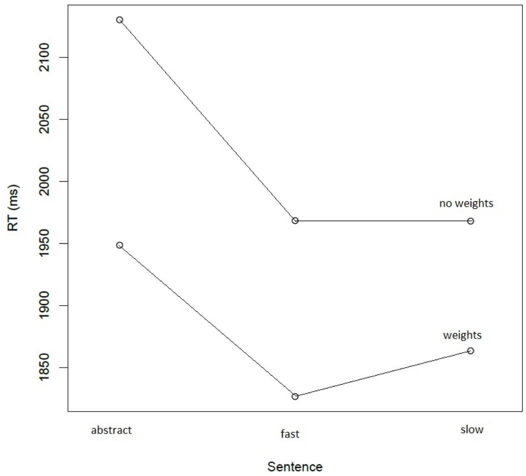

Figure 6-13. LME predicted response time for full-body sentences in Experiment 6-2.

6.2.2.3.2 Accuracy

In Model 1 abstract sentences were more accurate than slow sentences (β = -.55, z = 2.87, p < .01) but not fast sentences (β = -.62, z = 1.26, p = .21). There was no effect of weights (z <1) and no interaction of sentence type and weights condition when comparing only fast and abstract sentences (z <1) or slow and abstract sentences (β = .41, z = 1.45, p = .15). For Model 2, there was no difference between fast and slow sentences (β = .03, z = 1.64, p = .1) and no effect of weights (z <1). There was however a significant interaction between sentence speed and weights (β = .58, z = 2.01, p = .04).

In line with my hypothesis I found an interaction between weights condition and sentences speed such that when the speed of movement and speed of sentence match responses are more accurate.

LME predicted mean accuracy is displayed in Figure 6-14.

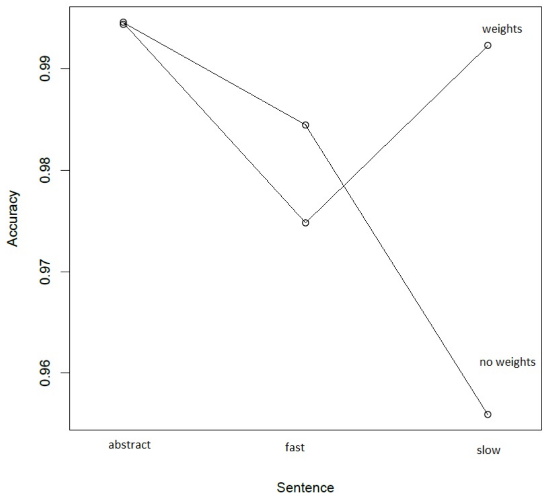

Figure 6-14. LME predicted accuracy for full-body sentences in Experiment 6-2.

6.2.2.4 Adverb sentences with abstract actions

This section presents an analysis of response time and accuracy for sentences describing abstract actions that are modified by adverbs (e.g. *Bob speedily thought over the business plan.*). By combining speeded adverbs with abstract actions I can test whether speed simulation can also be observed for actions that are not concrete. If speed is simulated then an interaction between sentence speed and weights condition is predicted.

6.2.2.4.1 Response time

Model 1 showed that responses to abstract sentences were significantly faster than both fast (β = .06, t = 2.33, p = .02) and slow sentences (β = .13, t = 3.58, p < .01). There was no effect of weights (t < 1) and no interaction between sentence type and weights when comparing abstract and fast (β = -.06, t = 1.64, p = .1) or abstract and slow (β = -.04, t = 1.32, p = .19). In Model 2, there was a marginal effect of weights (β = -.18, t = 1.89, p = .06) with responses faster when wearing weights compared to not wearing weights, but there was no difference between fast and slow sentences (β = .07, t = 1.26, p = .2) and no interaction (t < 1).

There was no support in response time for the predicted interaction between weights condition and sentence speed.

LME predicted mean response times are displayed in Figure 6-15.

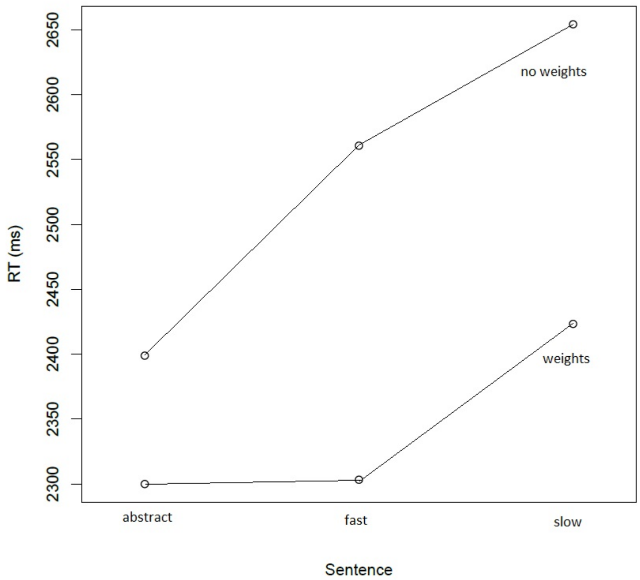

Figure 6-15. LME predicted response time for abstract sentences with adverbs in Experiment 6-2.

6.2.2.4.2 Accuracy

For Model 1 there was a significant effect of weights (β = 1.36, z = 2.55, p = .01) with responses more accurate when wearing weights compared to not. There was no difference between abstract sentences and fast (β = -.28, z = 1.23, p = .22) or slow sentences (β = -.66, z = 1.07, p = .28), no interaction between sentence type and weights when comparing abstract and fast (β = -.75, z = 1.79, p = .07) or abstract and slow (β = .41, z = 1.69, p = .09). In Model 2 there was a marginal difference between fast and slow sentences (β =-.59, z = 1.79, p = .07), but no effect of weights and no interaction (zs < 1).

Again, there was no support for the predicted interaction in accuracy measures. LME predicted mean accuracy is displayed in Figure 6-1.

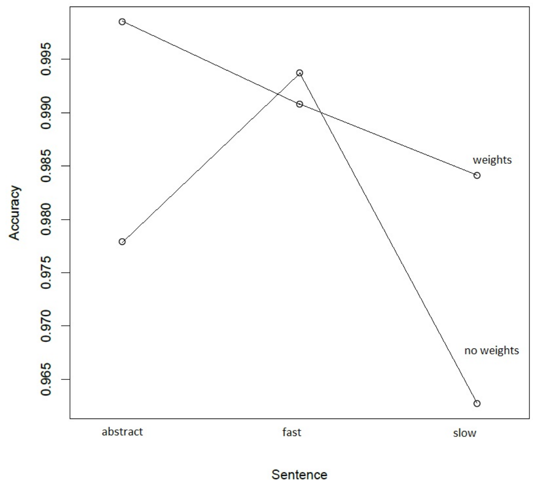

Figure 6-16. LME predicted accuracy for abstract sentences with adverbs in Experiment 6-2. Error bars reflect 1 standard error.

6.2.2.5 Adverb sentences with concrete actions

This section presents an analysis of response time and accuracy for sentences describing concrete actions that are modified by adverbs (e.g. *John speedily rolled up the sleeping bag.*). An interaction between sentence speed and weights condition is predicted.

6.2.2.5.1 Response time

For response time there was no difference between fast and slow sentences (t <1), no effect of weights (β = -.19, t = 1.46, p = .14) and no interaction (β = -.04, t = 1.17, p = .24).

There was no support in response time for the predicted interaction between weights condition and sentence speed. LME predicted mean response times are displayed in Figure 6-17.

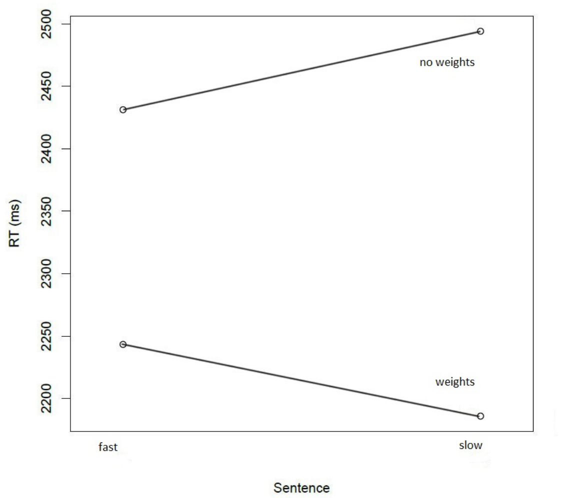

Figure 6-17. LME predicted response time for concrete sentences with adverbs in Experiment 6-2.

6.2.2.5.2 Accuracy

For accuracy there was no effect of sentence type, no effect of weights and no interaction (zs <1).

Again, there was no support for the predicted interaction in accuracy measures. LME predicted accuracy is displayed in Figure 6-1.

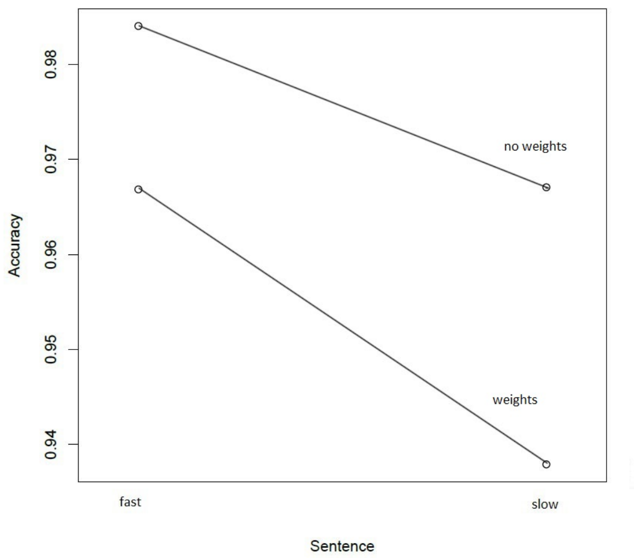

Figure 6-18. LME predicted accuracy concrete sentences with adverbs in Experiment 6-2. Error bars reflect 1 standard error.

Table 6-3. Summary of results Experiment 6-2. A single tick mark indicates a significant effect in response time and a tick mark within a box indicates a significant effect in accuracy. Only effects with *p*-values< 0.05 are included.

Hand sentences

	Model 1	**Model 2**
Weights		✓
Sentence Type		
Abstract vs. Fast		
Abstract vs. Slow		
Fast vs. Slow		
Weights * Sentence Type		
Abstract vs. Fast	☑	
Abstract vs. Slow		
Abstract vs. Speed	☑	
Fast vs. Slow		

Full-body sentences

	Model 1	**Model 2**
Weights		
Sentence Type		
Abstract vs. Fast	✓	
Abstract vs. Slow	✓	
Fast vs. Slow		
Weights * Sentence Type		
Abstract vs. Fast		
Abstract vs. Slow		
Fast vs. Slow		☑

Adverb sentences (abstract)

	Model 1	**Model 2**
Weights		☑
Sentence Type		
Abstract vs. Fast	✓	
Abstract vs. Slow	✓	
Fast vs. Slow		
Weights * Sentence Type		
Abstract vs. Fast		
Abstract vs. Slow		
Fast vs. Slow		

Adverb sentences (concrete)

	Model 1
Weights	
Sentence Type	
Fast vs. Slow	
Weights * Sentence Type	
Fast vs. Slow	

6.2.3 Discussion

Experiment 6-2 extends the investigation of speed simulation in comprehension of sentences to the action domain. Table 6-3 summarises the main results. In comparison to Experiment 6-1, which manipulated the speed of auditory footsteps during a sentence sensibility task, here I manipulated the speed of the participants' own physical movement before completing the sentence sensibility task. Participants had to move cans from one side of a table and back eight times whilst wearing arm and leg bands that either did or did not contain weights. Wearing weights made participants move more slowly than those not wearing weights.

Although a main effect of weights was only found in one model, overall, responses tended to be faster for those wearing weights than those not wearing weights. Although one may have expected responses in the sentence task to be slower wearing weights than not because weights made the movement task slower, there are reasons for why the opposite effect might have been found. First, on later consideration it was noted that the arm wraps containing weights were bulkier than the arms wraps with no weights in. This meant that resting their hands on the keyboard ready to respond in the sentence task was more awkward than without weights and hand posture was different to one people would naturally adopt (or to that adopted in those wearing wraps without weights). Faster reaction times may simply be due to a closer location of the fingers to the response keys in the weights condition compared to the no weights condition. Another explanation could be that participants were more eager to complete the task when wearing weights either because of being restricted to moving slowly in the movement task or due to the weights being uncomfortable during the sentence task, or both.

Response time to abstract sentences was longer than response time for fast and slow sentences in the full-body set. This replicated the concreteness effect observed in Experiment 6-1.

The most notable results, consistent with the hypotheses of the chapter, are that interactions between sentence type and weights condition were observed for hand sentences and full-body sentences. For hand sentences, accuracy was higher for both fast and slow sentences when wearing weights compared to not wearing weights. There was no difference in weights conditions for abstract sentences. Thus, being forced to move more slowly improves comprehension of hand action sentences. It seems likely however that this effect is not about speed of movement but rather movement effort or attention. Wearing weights makes movement more difficult and therefore requires more physical effort. Further, by making movement more difficult, participants may be focusing their attention on their movements and monitoring them more carefully than when they move freely without weights. This greater effort and attention will recruit the motor cortex to a greater extent, and thus it will be fairly active when comprehending the hand sentences, therefore facilitating their comprehension. In terms of the direction of this effect, one could hypothesise that if the movement task were being completed during the sentence task, wearing weights would make comprehension of hand sentences less accurate, because the motor system is strongly taxed by the movement task. Presenting the movement task first however means that it is no longer being recruited by real movement, but is still in an active state.

For full-body sentences, an interaction was observed such that responses were more accurate for fast sentences when not wearing weights compared to wearing weights, and responses to slow sentences were more accurate when wearing weights compared to not wearing weights. This reflects a match effect: responses are more accurate when speed of movement matches speed described in the sentence suggesting the speed in the motor system is simulated during comprehension of sentence describing speeded full-body actions.

In contrast to Experiment 6-1, no interaction effects were observed with adverb sentences. One explanation for this is that the current experiment is underpowered. Firstly, the weights factor is a between subjects manipulation whereas the footsteps factor was a within subjects manipulation. Further, Experiment 6-1 contained two presentations of each sentence but here there was only one. A more sensitive analysis could be to include movement times from the movement task as a predictor, rather than using the categorical variable “weights” versus “no weights”. However, this would only have been plausible if the weights manipulation was a within-subjects manipulation, because a movement time across the two conditions is very variable.

For example, a strong male wearing the weights may still have completed the task more quickly that a small female not wearing weights, simple based on their physical ability.

6.3 General Discussion

The first aim of the work in this chapter was to address whether speed simulation is observed in sentences describing fast and slow actions. I used a sentence sensibility task to ensure that participants fully comprehended the meaning of the sentence without drawing attention to the semantic domain of investigation. The results of the studies described here show that comprehenders do simulate speed of actions as described in sentences that are part of events involving agents and goals.

Another aim of the present set of experiments was to investigate different types of speeded actions (hand/arm actions, full-body actions, abstract actions) and different ways of describing speeded actions in language (verbs and adverbs). Within the chapter there is evidence for speed simulation in all action types and using both adverbs and verbs, but there are differences between the different types of simulation. Suggestive evidence for auditory simulation of speed was provided for hand/arm action sentences and full-body by combining sentences with the sound of fast and slow footsteps. A marginal interaction was found such that responses were more accurate when speed of action described in the sentence matched the speed of auditory footsteps played simultaneous with sentence presentation for sentences describing hand/arms actions and abstract sentences. An marginal interaction was also found for sentences describing full body actions but the direction of effect was different: responses were less accurate when speeds matched. This suggests that simulations used to comprehend these sentences included specific features about the effector used in the action (i.e. hands, arms). This is in line with imaging evidence showing that action words activate the motor and premotor cortex in an effector-specific way (Hauk et al., 2004). When the sentence described action with the whole body, the simulation matched the auditory footsteps in terms of actions features (leg movements) and speed. This large overlap in features led to interference between sentence and sound that led to lower accuracy. When the sentence described actions with the hands/arms, the simulation matched the auditory footsteps in terms of only speed and not action features. Since there was only partial overlap in features, responses were facilitated and hence more accurate. If it were possible to create an auditory stimulus that reflected hand/arm actions, then I would expect the opposite pattern of results. For example, one could combine the sound of clapping with sentence presentation.

Evidence for simulation of speed in action was found for full-body sentences in Experiment 6-2. Accuracy for full-body sentences was higher when the speed described in the sentence matched the speed in which participants had been moving during the movement task (e.g. fast sentence meaning and no weights condition). This suggests that the movement task activated motor processes in a way that is sensitive to the speed of movement. These processes overlapped with those involved in simulating speeded full-body actions during sentence comprehension, which led to greater accuracy.

I also found evidence for action simulation with hand/arm sentences, but this simulation was not sensitive to speed implicit in the sentence. Responses to fast and slow hand sentences were more accurate after wearing weights than not wearing weights, but there was no such difference for abstract sentences. This effect was not predicted but there are possible post hoc explanations. Wearing the weights led to slower movements and possibly more difficulty and effort. The greater effort may have taxed the motor system to a greater extent, thereby making it more active at the time of sentence processing and leading to facilitation of responses to action sentences in general. An alternative is simply that the movement task took longer when wearing weights compared to not wearing weights, and this longer duration activated the motor cortex to a greater extent. However, according to these explanations a similar effect of weights on accuracy should be seen for full-body sentences as well, which is was not. It may be the case though that simulations evoked by fast and slow full-body sentences differ in speed to a greater extent than simulations evoked by fast and slow hand actions, or that speed is more salient in full-body actions than hand actions, meaning that the speed of physical movement would not affect comprehension of hand actions sentences. A final possibility is that wearing the weights did not slow down hand/arm actions, but the difference in movement times is due to slower leg movements when wearing weights compared to not wearing weights. Participants were instructed to pick up a can, move to the other end of the table and then place the can in its position. Therefore, the hands and arms may have mostly been used for grasping and releasing actions, which is not slowed by weight, and the movement between the ends of the table was done by the legs/feet. Wearing the weights on the wrist may still have activated the motor cortex to a greater extent compared to not wearing weights because the system is aware that more effort would be needed for action preparation and execution. However, this activation would not be in terms of speed because few fast or slow hand/arm movements had been made. This explanation seems most plausible based on the effects found with full-body sentences and the fact that speed simulations were observed for hand action sentences in Experiment 6-1.

For adverb sentences with both concrete and abstract actions, no interaction between sentence speed and weight condition was found. This suggests that speed described by adverbs does not lead to speed action simulations. In fact there was no specific effect of wearing weights on comprehension of fast and slow sentences compared to abstract sentences, which suggests that a general action simulation did not occur. One explanation for the difference between speed effects with adverbs and verbs is that speed information is tied to action information with a verb, but speed information is outside of the action with an adverb. This raises the question then of what the function of adverbs is if semantic features are more successfully simulated, or accessed, with verbs. Another possible explanation is that the adverbs used in this experiment also evoked a number of other semantic features. Compared to the adverbs “quickly” and “slowly”, there are a variety of other adverbs, for example “reluctantly” and “frantically”, that may evoke simulations of other features more strongly, such as emotion and facial expression. Thus, speed simulations may be weaker and harder to detect amongst these other aspects of the simulations.

A final point of discussion for the present chapter is why interaction effects were observed in accuracy measures and not response time, which is where embodied effects are typically observed. If comprehension of speed in language partially but not completely overlaps with systems involved in speed perception, then I would expect their combination to affect processing to the extent that it would be interfered with or facilitated in terms of the temporal nature of the correct process. That differences were observed in accuracy suggests that the interaction affects whether or not the process is successfully completed. One reason for this could be that the present experimental task is fairly difficult. Many of the “nonsense” sentences could be given a metaphorical or poetic description if one was so inclined, and therefore responding “sensible” is more difficult than responding “yes” in the lexical decision task of Chapter 4. For example “*Diane framed the zoo’s rain*” could be interpreted as describing a photograph of rain, rather than a nonsense sentence. Therefore, accuracy here is more sensitive to influence and anything the comprehension system detects as odd, such as mismatch between speed stimuli and speed in the sentence, or large overlap between the two, could lead to incorrect responses. Embodied effects were observed in accuracy measures elsewhere when directional supra-threshold motion (consciously perceived) was presented at the same time as a lexical decision task on directional verbs, but not when the motion stimuli was sub-threshold (not consciously perceived) (Meteyard et al., 2008). Here responses were less accurate to all motion verbs compared to control verbs. The authors suggest that the irrelevant supra-threshold stimuli were suppressed by higher-level mechanisms, which led to disruption of semantic processing. However, when the motion stimuli are less salient the suppression mechanism is not activated. This explanation does not seem to apply here because effects were different for matching and mismatching speeds, rather than affecting speed sentences in general (except for hand sentences in Experiment 6-2). However, a similar argument could be used to explain the present findings in which responses are less accurate when real-world speed (footsteps or action) is incongruent with the sentence speed. The speed stimuli are suppressed because they are irrelevant to the present comprehension of the sentence, which disrupts semantic processing. This explanation however cannot explain the higher accuracy for mismatching full-body sentences in Experiment 6-2 and hence further investigation is required.

6.4 Chapter conclusion

The present chapter has provided evidence for speed simulation when comprehending sentences describing fast and slow full-body actions and fast and slow hand actions. Further, simulations are observed when speed is encoded both in verbs and in adverbs. The simulations evoked include auditory speed and speed of action, and as suggested in Chapter 4, include specific details about the effector used in the action. Differences were observed in accuracy and not response time, which could suggest that the task was particularly difficult or that the comprehension system was dealing with the irrelevant speed stimuli in a particular way that led to disruption of processing.

Chapter 7 Eye-movements and the mental simulation of sentence speed

In this chapter I continue to focus on speed in sentence comprehension. The experiments here build upon those in the previous chapter by combining spoken sentences with visual scenes that contain static depictions of a described event. Thus, the comprehension process will involve mapping the incoming linguistic information onto the visual scene. Additionally, I use eye tracking to monitor comprehension. This means that I can measure simulation without requiring participants to make explicit judgments about the sentences. This allows the online measurement of simulation in a more naturalistic manner and provides temporal information that is not available from coarse measurements such as reaction time.

Many studies have demonstrated the link between language input and eye-movements (for review see Altmann & Kamide, 2004). Such studies have used the 'visual world paradigm' in which participants are presented with visual scenes containing sentence referents at the same time as spoken linguistic stimuli (see Heuttig, Rommers & Meyer, 2011). The combination of visual scene and linguistic input allows one to track the comprehension process at a fine temporal grain. Studies have shown that eye-movements towards reference objects are time-locked to incoming linguistic information (e.g. Allopenna et al., 1998). Tracking eye-movements allows one to look closely at the underlying processes occurring during language processing. For example, using eye-tracking and presenting readers/listeners with garden path sentences (ambiguous sentences that lead comprehenders to initially parse the sentence incorrectly e.g. *The horse raced past the barn fell*) can indicate which sentential interpretations are being considered and ascertain the point at which ambiguity resolution occurs (Ferreira, Engelhardt & Jones, 2009). Similarly, eye-movements have shown that comprehenders are able to predict upcoming items in sentences or events: when participants listened to highly constrained sentences and corresponding visual scenes they were more likely to look towards an object before it was mentioned than toward distractors compared to unconstrained sentences and scenes (Altmann & Kamide, 1999).

When employing eye tracking to study mental simulation, first, it is critical to note that simulation can be assessed without requiring dual-task designs where the presence of mental simulation is inferred by the existence of interference/facilitation effects (e.g. Glenberg & Kaschak, 2002, Zwaan & Taylor, 2006 and Chapters 4 and 6 of this thesis). Second, looking behaviour during language processing reflects a low-level aspect of cognition that is most often outside of voluntary control (Richardson & Spivey, 2000). For example, in a model of saccade generation, voluntary eye-movements have been described as "unusual" (Findlay & Walker, 1999). Further, studies looking at the processing of words in the presence of phonological competitors (e.g. *candy* and *candle*) show that participants often saccade to a phonological competitor in a visual scene but are unaware of doing so (Tanenhaus, Spivey-Knowlton, Eberhard & Sedivy, 1995).

Eye-movements observed while attending to a visual scene and comprehending language are thought to reflect sensorimotor patterns learned from experience with events in the world. That is, sensorimotor content of sentences (such as motion information) can influence the direction of visual attention and its interaction with visual properties of the scene (Mishra & Marmolejo-Ramos, 2010). Perceptual simulations generated during language comprehension and indexed by eye-movements are consistent with the view that language develops in support of situated action (Barsalou, 1999b; Glenberg & Gallese, 2011).

Previous studies have shown that eye-movements can reveal the unfolding of mental simulations. Spivey and Geng (2000) found that when participants listened to narratives describing movement in a certain direction, eye gaze was directed more to the corresponding area of a blank screen than other areas. For example, when listening to a description of a person descending into a canyon, a greater proportion of looks were directed to the bottom of the screen than elsewhere. Eye-movements have also been shown to reflect implied motion in both sentences, such as sentences with fictive motion "*The road goes through the desert"* (Richardson & Matlock, 2007) and pictures, such as a cereal box over a bowl where the falling of the cereal is implied (Coventry et al., 2010). Low-level motor mechanisms involved in perceiving an event become activated by the corresponding visual representation activated through imagining that same event. Spivey, Richardson & Gonzalez-Marquez (2005) describe the function of eye-movements in such cases as doing "some of the work involved in the "high-level" cognitive act of visual imagery elicited by linguistic input". Critically, in this view, the motor processes involved in visual perception are thought to be intrinsic components of the mental state rather than a separate function and therefore a necessary component of the comprehension process (Spivey & Geng, 2000).

In this chapter I look at how speakers direct their eye gaze to static scenes while listening to sentences describing slow or fast motion events. A similar approach has been used by Richardson and Matlock (2007), in which speed was indirectly manipulated using descriptions of motion traversing easy (*The desert is flat)* versus difficult (*The desert is hilly*) terrain. In their study, participants spent more time looking at a path region of a visual scene for fictive motion sentences that followed a description of a difficult terrain compared to an easy terrain, suggesting that listeners developed a mental representation of motion along the path.

If speakers simulate the speed of events, events described as having different speeds should differ with respect to the *duration* of the corresponding simulation. Because of the interactive processes between language comprehension, world knowledge and visual attention (Altmann & Kamide, 2004; Crocker, Knoerfele & Mayberry, 2010; Heuttig et al., 2011), this difference in duration of simulation should then be reflected in the low-level visual processes engaged in eye-movement control, with looking times to objects in a supporting visual scene being longer for events described as being slow than for events described as being fast.

7.1 Experiment 7-1

The first experiment contrasted events described by “slow” verbs (e.g. *amble*) and “fast” verbs (e.g. *dash*) and events in which speed was manipulated with the adverb “*quickly*” or “*slowly*”, in spoken sentences, accompanied by matching visual scenes. The aim was to assess whether listeners looked for longer/shorter durations at objects in the scene depending upon the speed of verb/adverb. In addition the speaking rate (fast vs. slow) of the sentence was manipulated. This was done mainly as a manipulation check: differences in eye-movement behaviour between fast and slow speech would be expected simply because there will be more time to look around the scene for sentences that are spoken slowly compared to sentences spoken quickly. In addition, any interaction between speaking rate and speed of the verb would also be theoretically important suggesting that processing semantic features of speed words and processing differences in physical speed of language production engage overlapping processes. That is, understanding the meaning of *speed* described in the sentences may involve similar systems to those involved in processing the auditory *speed* of the sentences (i.e. speed perception), and combining these two types of speed may affect processing differently when the speeds match compared to when they do not match. This effect is similar to that observed in Chapter 6 when speeded footstep sounds affect comprehension of sentences about speeded actions. There could also be differences in the extent to which simulation occurs for fast and slow speech. Some researchers argue that simulation is a slow process and thus does not fully develop all of the time (Barsalou et al., 2008; see Chapter 1 section 1.4.4.). Comprehension that requires quick or shallow understanding (for example in noisy situations or under time pressure) may rely more heavily on processes such as statistical linguistic patterns (Louwerse & Jeuniaux, 2010). Thus, there may be evidence of simulation for sentences that are spoken slowly but not for sentences that are spoken quickly.

7.1.1 Method

7.1.1.1 Participants

Forty-four[10] native English speakers with normal or corrected-to-normal vision (29 females, mean age = 24.1) were recruited from the UCL Psychology Subject Pool and were paid for their participation. Four participants were removed for having an insufficient number of looks to any of the objects in the scene.

7.1.1.2 Material

Experimental items were spoken sentences describing either a fast or slow event, for example "*The lion ambled/dashed to the balloon*". Sixteen fast verbs (e.g. *dash*) and 16 slow verbs (e.g. *amble*) were used in sentences (verb sentences) and had previously been rated as to their implied speed by a separate group of participants (see chapter 4 section 4.3.1.2.1). Additionally, the adverbs *quickly* and *slowly* were used (adverb sentences) and were paired with 25 verbs that were rated as neutral in terms of speed in norming procedure described in section 4.3.1.2.1. This made 41 experimental items in total. Fast, slow and neutral verbs used in the sentences are displayed in Table Appendix 1-1, 1-2 and 1-3.

The speaking rate of each sentence was also manipulated to be either fast (average of 222 words per minute) or slow (average of 116 words per minute). Each experimental item therefore had four versions; a slow event with a slow speaking rate, a fast event with a fast speaking rate, a slow event with a fast speaking rate and a fast event with a slow speaking rate. Each participant heard only one version of

[10] Number of participants was estimated roughly based on previous work with speed manipulations (Fecica & O'Neill, 2010). Note that a limitation of the chapter could be the unequal sample size across experiments (i.e. Experiment 7-2). The additional subjects were tested to check that an observed result was not a false positive.

each item. Thus there were four versions of the experiment with items allocated to each using a Latin Square design. Forty-one filler sentences were created that described either motion of no specific speed or no motion (e.g. "*The moose approached the box*") or no motion (e.g. "*The bird spotted the tree*").

Sentences were recorded by a speaker with an English accent in a soundproof room and spliced so that sentences with the same speaking rate were identical except for the speed verb or adverb, with the resulting sentences sounding natural. For example, in the recording of "*The lion ambled to the balloon*", "*dashed*" would be inserted into the sound file in the place of "*ambled*". Mean duration of sentences was 3667ms (*SD* = 242ms) for slow speaking rate and 1777ms (*SD* = 145ms) for fast speaking rate for verb sentences, and 3455ms (*SD* = 206ms) for slow speaking rate and 1821ms (*SD* = 149ms) for fast speaking rate for adverb sentences

Each experimental item was paired with a visual scene that included the agent and target destination of the sentence and a distractor destination (see Figure 7-1A for an example). The distractor destination was included because participants' task was to click on the correct target destination. Individual pictures were taken from a collection of pictures used in previous projects in the lab and edited and placed in a scene using Paint.net. The agent was located at the centre of the scene connected by a path to the target destination and the distractor destination located on the left or right side, counter-balanced across trials.

7.1.1.3 Procedure

Before beginning the experiment participants completed a 'Mouse Training' task in which they had to click on circles on the screen for approximately two minutes. This task was included in order for participants to feel comfortable with the mouse and to give them practice at clicking on objects in an experimental setting.

In each trial, participants first had to look at the centre of the screen as a drift correction check and then had to click on a fixation cross to ensure that mouse position was central at the beginning of the trial. The visual scene was then presented for 1000ms after which the sound file was played whilst the scene remained onscreen. Participants had to use the mouse to click on the last object mentioned in the sentence. After 25% of filler trials comprehension questions were presented on screen such as "*Did the moose go to the box*?" and participants were to respond pressing the left mouse button for "yes" and the right mouse button for "no". Six practice trials were completed first. See Figure 7-2 for an example trial. Note that the mouse task and comprehension questions were not of primary interest as dependent variables, but rather served as an incentive for the participants to listen carefully to the sentences.

Eye-movements were recorded using an Eyelink 2 head-mounted eye-tracker. The experiment lasted around 25 minutes.

A **B**

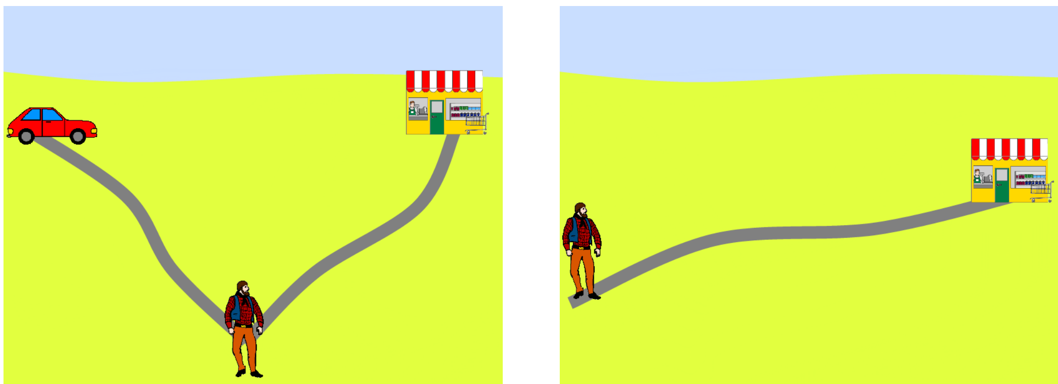

Figure 7-1. Example scene with (A) and without (B) for the sentence "*The man zoomed to the shop*"

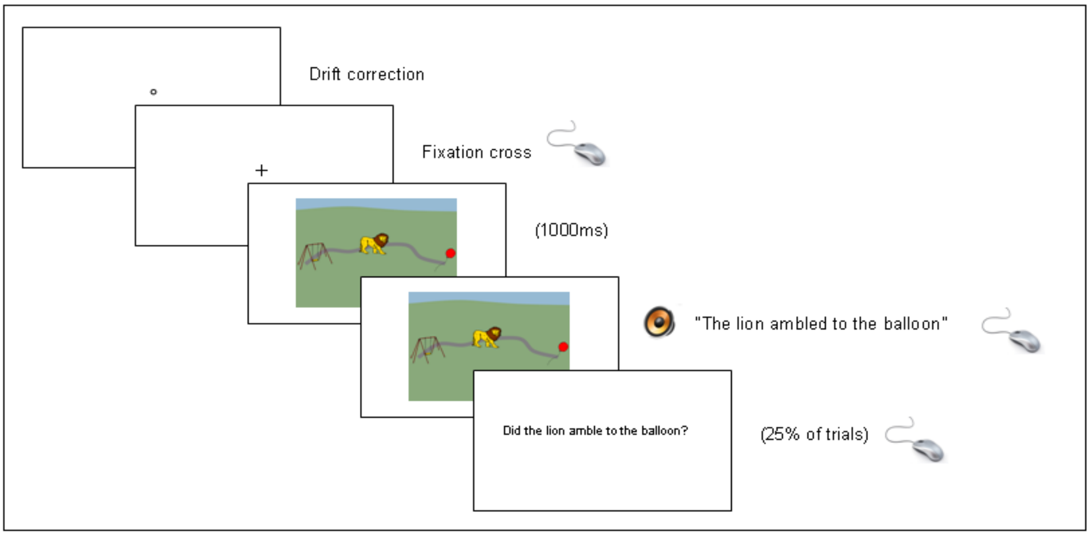

Figure 7-2. Example trial in Experiment 7-1.

7.1.2 Results

Eye-movements were recorded from the onset of the spoken sentence to the time at which they clicked on the target destination. As part of a data cleaning process fixation times less than 150ms were removed from analysis (< 5%). Interest areas were created for the agent and destination objects in the scene and looks to these areas were analysed. If participants simulate speed during spoken comprehension then I would expect looking time towards objects in the scene to differ between sentences describing fast and slow events. Analyses on response time to click on the target destination can be found in the Appendix section A3.1.

7.1.2.1 Dwell time

The total dwell time across the whole trial on the agent and target destination of the sentence was calculated for verb sentences (Figure 7-3) and adverb sentences separately (Figure 7-4); this is the total time in a trial spent looking at each object.

7.1.2.1.1 Looks to the agent

For looks to the agent (Figure 7-3A (verbs) and 7-4A (adverbs)), an LME controlling for verb/adverb frequency (taken from the English Lexicon Project (ELP); Balota et al., 2007) and duration (in ms) of each verb/adverb found no main effect of speed of verb (β = .09, t = .68, p = .5) or adverb (β = .04, t = 1.12, p = .32), but did find a main effect of speaking rate for both sentence types (verbs: β = -.43, t = 6.11, p < .001, adverbs: β = -.20, t = 2.21, p = .03); dwell time on the agent was longer for sentences with a slow speaking rate than sentences with a fast speaking rate. This result however, is not theoretically interesting; it simply reflects that for sentences with a slow speaking rate, there was more time during a trial for the eyes to explore the scene. Results also showed a marginally significant interaction between speed of verb and speaking rate (β = -.06, t = 1.94, p = .05) for verb sentences. Planned comparisons showed that for sentences spoken slowly, dwell time on the agent was longer for sentences with slow verbs than for sentences with fast verbs (β = .02, t = 2, p = .04), but there was no difference between sentences with slow verbs and sentences with fast verbs for sentences spoken quickly (β = .11, t = 0.51, p = .61). No significant interaction was found for adverb sentences (β = -.04, t = 1.6, p = .11).

7.1.2.1.2 Looks to the destination

For looks to the destination (Figure 7-3B (verbs) and 7-4B (adverbs)), an LME controlling for word frequency and duration (in ms) of the verb/adverb there was again a significant effect of speaking rate in which dwell time was longer for sentences with a slow speaking rate than sentences with a fast speaking rate (verbs: β = -.20, t = 3.04, p < .01, adverbs: β = -.33, t = 2.37, p = .02). For adverb sentences there was no effect of adverb speed (β = -.06, t = .57, p = .59) and no interaction between adverb speed and speaking rate (β = .02, t = .78, p = .47). For verb sentences, there was no main effect of verb speed (β = -.02, t = .58, p = .58,) and in contrast to the analyses for looks to the agent, no interaction (β = -.02, t = .54, p = .53).

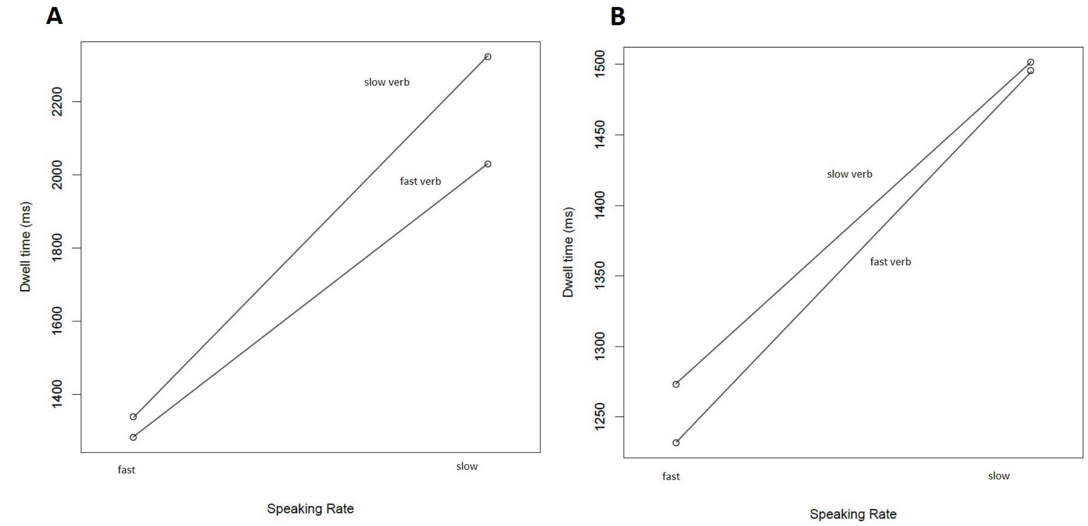

Figure 7-3. LME predicted mean dwell time on agent (A) and destination (B) for verb sentences in Experiment 7-1. Error bars reflect 1 standard error.

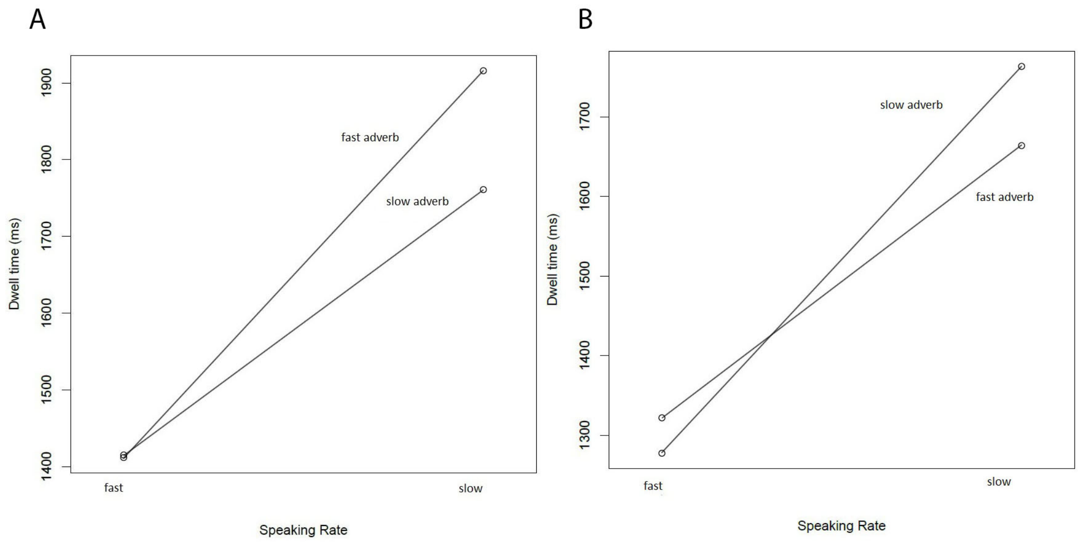

Figure 7-4. LME predicted mean dwell time on agent (A) and destination (B) for adverb sentences in Experiment 7-1. Error bars reflect 1 standard error.

7.1.3 Discussion

An interaction was found between speaking rate and verb speed for dwell time on the agent; for sentences with a slow speaking rate, dwell time was longer for slow verbs than for fast verbs, whereas within sentences with a fast speaking rate, dwell time was similar for fast and slow verbs.

These results suggest that listeners mentally simulated the speed of motion of the agent and thus looked at the agent for longer for slow verbs than fast verbs, at least for sentences spoken slowly, because this event would take longer to unfold in the real world. The lack of such effect in the fast speaking rate condition is consistent with the idea that simulations take time to develop (Barsalou, Santos, Simmons & Wilson, 2008; see Chapter 1 section 1.4.4.). Thus, it is possible that the duration of the sentences in the fast speaking rate condition was too fast for simulations to completely develop or alternatively, the duration was too short for the simulation to be observed in the eye-movement recordings (i.e. the time to view the scene was not sufficient). The simulation of speed was not reflected in time to click on the target destination, which was only affected by speaking rate.

Experiment 7-1 found no difference between fast and slow events when described with adverbs. This may suggest that verbs and adverbs do not describe the speed of an event in the same way. However, there may be alternative explanations for this result. First, there was a high degree of repetition of adverbs in the experiment (only two adverbs were used for a total of 25 sentences). Further, there are aspects of the task and configuration of the visual scene that may have led to the observed simulation effect occurring for verb sentences and not adverbs sentences. These differences may also account for why the effect was found only on the agent of the sentence, and not the destination, as described below. To investigate this suggestion, and to replicate the general finding, I ran a second experiment with a change of task and scene type.

7.2 Experiment 7-2

Experiment 7-1 provided the first demonstration that slow and fast verbs lead to different patterns of eye-movements. However, it could be argued that the task (clicking on the target destination) could have reduced simulation-driven eye-movements towards the target destination while participants comprehended the final part of the sentence, as they were more focused on quickly completing their task. Such a strategy could lead to shallow processing of the agent and the adverb. Alternatively, it may be that the target destination was ambiguous due to the presence of the distractor and therefore participants continued to look towards the agent instead of a destination that they were unsure about. In order to better understand why effects of verb speed were observed on the agent and not on the destination, I carried out a second experiment in which the mouse-clicking task and the distractor object were removed. In Experiment 7-2 participants were to listen to the sentences whilst viewing the scenes, with comprehension questions asked on every trial, focusing on the destination of the sentence. Additionally, on some trials, a verb would appear onscreen and participants had to decide whether that verb had been used in the sentence or not. The new task was intended to force participants to encode all aspects of the sentence.

7.2.1 Method

7.2.1.1 Participants

Fifty-two native English speakers with normal or corrected-to-normal vision (29 females, mean age = 24.3, *SD* = 4.58) were recruited from the UCL Psychology Subject Pool and were paid for their participation.

7.2.1.2 Material

A new set of scenes was created for all experimental trials and fillers (Figure 7-1B), as the distractor object was no longer necessary. The location of the agent and destination in the scene was counterbalanced across trials (either on the left or right of the scene).

The same set of sentences as Experiment 7-1 was used as well as an additional set of sixteen verb sentences created by taking each verb from Experiment 7-1 and placing them in a sentence with a new agent and destination, to allow more statistical power.

This meant that each participant now saw eight items in each condition. Sixteen new filler trials were added so that the number of experimental trials and filler trials was equal (see Appendix section A2.2.2. for new items and fillers).

7.2.1.3 Procedure

The procedure was the same as Experiment 7-1 except participants were no longer required to click on the target destination. The visual scene remained on screen until 1500ms after sentence offset. The participant would then either be presented with a comprehension question or presented with a verb to which they had to decide if it had been used in the sentence, followed by a comprehension question. Participants responded with the mouse as before. The procedure is visually exemplified in Figure 7-5.

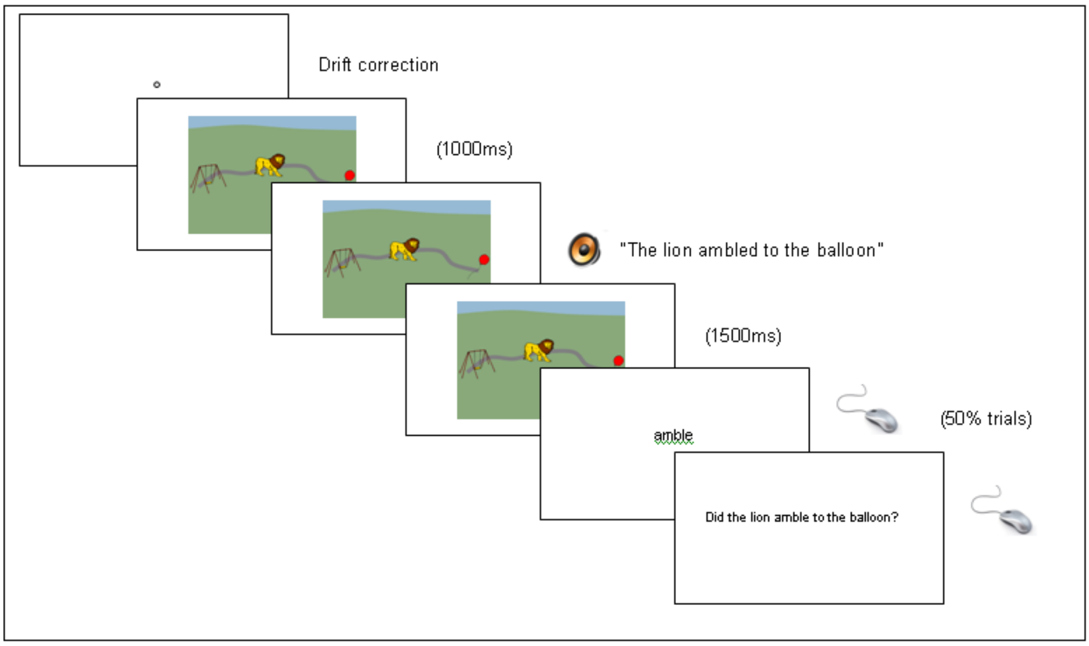

Figure 7-5. Trial procedure in Experiment 7-2.

7.2.2 Results

Data extraction proceeded in the same way as Experiment 7-1. Analyses of response time and accuracy to comprehension questions can be found in the Appendix, section A3.2.

7.2.2.1 Dwell time

Three verb sentences were removed from analysis due to a coding error. As in Experiment 7-1, the total dwell time across the whole trial on the agent and destination of the sentence was calculated. Again, if speed is simulated then I expect looks towards objects in the scene to be longer for sentences describing slow speed compared to fast speed. Further, if simulation of speed is hindered when sentence speaking rate is fast, as suggested by the results of Experiment 7-1, then an interaction between verb/adverb speed and speaking rate is predicted such that differences between fast and slow verb/adverb sentences are observed only for sentences spoken slowly.

7.2.2.1.1 Looks to the agent

For looks to the agent (Figure 7-6A (verbs) and 7-7A (adverbs)), an LME controlling for word frequency and duration (in ms) of each verb/adverb did not find a main effect of speed of verb (β = .01, t = .54, p = .59) or adverb (β = -.04, t = .26, p = .79). For verb sentences there was a main effect of speaking rate (β = -.33, t = 6.65, p < .001); dwell time on the agent was longer for slow speaking sentences than fast speaking sentences, but there was no effect of speaking rate for adverb sentences (β = -.14, t = .97, p = .33). There was no interaction between speaking rate and speed of verb (β = .01, t = .32, p = .75) or between speaking rate and speed of adverb (β = .02, t = .89, p = .37).

7.2.2.1.2 Looks to the destination

Average dwell times on the destination object are shown in Figure 7-6B (verbs) and 7-7B (adverbs). Using a linear-mixed effects model including frequency and duration (in ms) of each verb/adverb as predictors there was no main effect of speed of verb (β =-.02, t = 0.91, p = .37) or adverb (β = -.06, t = .95, p = .34) but there was a main effect of speaking rate (verbs: β =-.29, t = 4.9, p < .001, adverbs: β = -.47, t = 3.9, p < .001); dwell time on the destination was longer for slow than fast speaking sentences. There was also a significant interaction between speed of verb and speaking rate (β = .05, t = 2.18, p = .03) for verb sentences. Planned comparisons showed that for sentences spoken slowly, dwell time on the destination was longer for sentences with slow verbs than for sentences with fast verbs (β = -.11, t = 2.01, p = .04), but there was no difference between sentences with slow verbs and sentences with fast verbs for sentences spoken quickly (β = .07, t = 1.66, p = .1). There was no interaction between speed of adverb and speaking rate (β = .01, t = .36, p = .72).

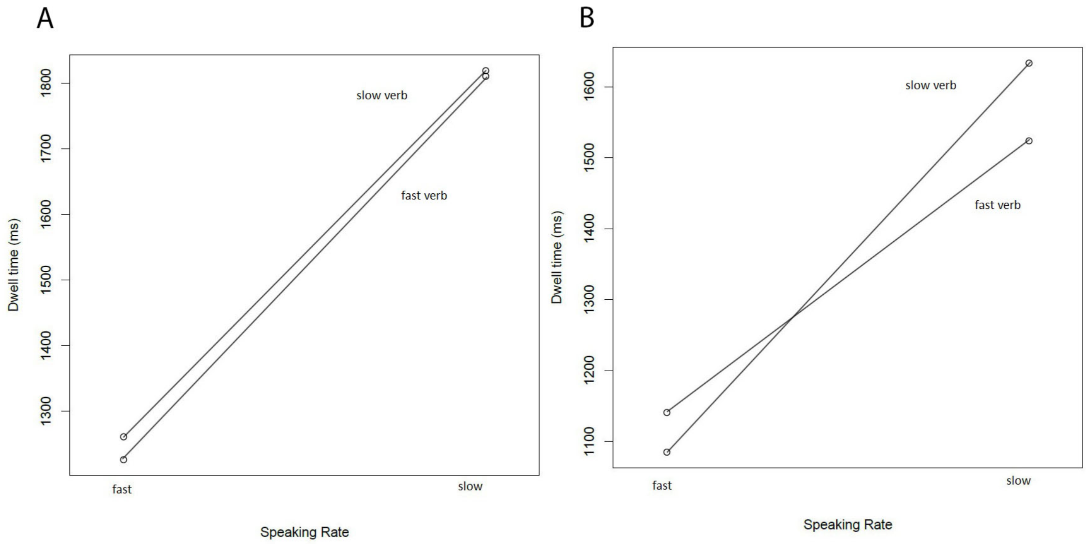

Figure 7-6. LME mean predicted dwell time on agent (A) and destination (B) for verb sentences in Experiment 7-2. Error bars reflect 1 standard error.

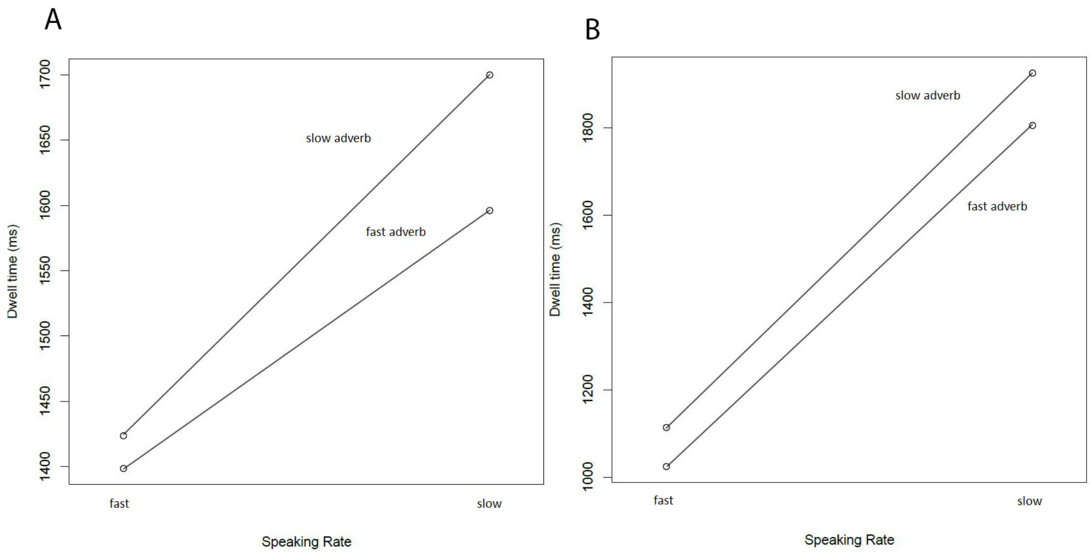

Figure 7-7. LME mean predicted dwell time on agent (A) and destination (B) for adverb sentences in Experiment 7-2. Error bars reflect 1 standard error.

7.2.3 Discussion

In contrast to Experiment 7-1, Experiment 7-2 showed an effect of verb speed on the *destination*, *not* the agent. Differences between the task and visual scenes in the two experiments may be responsible for this difference in results. First, in Experiment 7-1, participants had to click on the destination as soon as they could identify it, possibly cutting short time spent looking at the target destination but in Experiment 7-2 participants were free to view the scene until 1500ms after sentence offset. Second, in Experiment 7-2, the destination was always known since there was no longer a distractor destination present in the scene. Thus, participants could look towards the destination while completing the simulation of the event whereas in Experiment 7-1 the agent was the only certain object involved in the event up until hearing the name of the destination. Importantly and more generally, the results suggest that the online simulations developed by listeners and indexed by eye movements are not fixed but can develop in a flexible way depending on the task and the information that is available at any given time. However, given the differences in procedure between Experiment 7-1 and Experiment 7-2, I cannot exclude at this point other possible accounts. Therefore, Experiment 7-3 presents a replication of both experiments within subjects in order to assess whether differences emerge as a result of differences in the visual scene and task. Since there were no effects using the adverbs "*quickly*" and "*slowly*" I decided to remove them from Experiment 7-3, and further investigate them separately in Experiment 7-4.

7.3 Experiment 7-3

Both Experiment 7-1 and 7-2 provide evidence that the speed described by verbs in a sentence affects looking behaviour towards depicted objects, when the sentence is spoken slowly. However, depending on the configuration/content of the scene, the effect appears to differ: verb speed affects how long listeners will look at the agent when there is more than one destination, whereas verb speed affects looks to the destination when it is clear where the agent will end up. This difference invites the speculation that simulations used during language comprehension are dynamic and changeable, developing in the way most appropriate for the on-going task.

In Experiment 7-3, I assess whether the simulations developed during the task dynamically adapt to differences in the visual scene by combining the major differences between Experiment 7-1 and 7-2. In this experiment, I directly manipulated the scene type (with a distractor as in Experiment 7-1 or without a distractor as in Experiment 7-2) while keeping the task the same as Experiment 7-2 (including the additional 1500ms after the sentence offset). I expect to replicate the effect of speed of verb on dwell time on the target destination for scenes without a distractor, like in Experiment 7-2. The prediction for scenes with a distractor is not as clear. Having two possible target destinations means that there is still ambiguity in the scene, however, since the task demands of Experiment 7-1 have been removed (i.e. of clicking on the target destination as soon as possible), participants may not be strategically focusing on the agent and it may be the case there will be no differences between fast and slow sentences.

7.3.1 Method

7.3.1.1 Participants

Forty native English speakers with normal or corrected-to-normal vision (20 female, mean age = 24.25, *SD* = 6.94) were recruited from the UCL Psychology Subject Pool and paid for their participation.

7.3.1.2 Material

In order to establish the generalizability of the findings beyond the specific agent-verb pairing used in Experiment 7-1 and 7-2, a new set of 16 experimental sentences were created using the same 16 fast and slow verbs from the previous experiments, but combined with different agents and destinations (see Appendix section A2.2.3). Sentences were recorded at a normal speaking rate (average 144 words per minute). Average sentence duration was 2498ms. Each sentence had two versions (fast and slow verb) and each participant now heard both versions (separated into two blocks). For each experimental item, four versions of each scene were created combining scene type (double or single) and location of the target destination (left or right). Each participant saw the same scene type for each sentence version, but with the location counterbalanced. For example, one participant may listen to sentence 1 with a fast verb combined with a single scene with the target destination of the left in the first block, and then listen to sentence 1 with a slow verb combined with a single scene with the target destination on the right in the second block. There were 32 filler sentences, half were paired with a scene that included a distractor and half were paired with a scene without a distractor.

7.3.1.3 Procedure

Participants were required to listen to the sentences and then answer comprehension questions that were presented on the screen. Responses were made with the mouse as before.

7.3.2 Results

Data extraction proceeded in the same manner as the previous two experiments. Analyses of response time and accuracy to comprehension questions can be found in the Appendix, section A3.3.

7.3.2.1 Dwell time

As in the previous two experiments, the total dwell time across the whole trial on the agent and destination of the sentence was calculated (see Figure 7-8).

7.3.2.1.1 Looks to the agent

For looks to the *agent* (Figure 7-8A), an LME controlling for word frequency and duration (in ms) of each verb did not find a main effect of speed of verb (β = -.03,t = .35, p = .73) nor an interaction between verb speed and scene type (β = .01, t = .61, p = .54). There was however, a main effect of scene type (β = .10, t = 6.93, p <0.001), with longer dwell time on the agent for scenes containing a distractor, than scenes without distractor.

7.3.2.1.2 Looks to the destination

Average dwell times on the *destination* are shown in Figure 7-8B. Using an LME including frequency and duration (in ms) of each verb as predictors there was no main effect of speed of verb (β =-.01, t = 1.17, p = .24) but there was again a main effect of scene type (β =-.31, t = 6.93, p < .001) with longer dwell time on the destination for scenes with no distractor than scenes with a distractor. There was also a significant interaction between speed of verb and scene type (β = .06, t = 2.49, p = .01): dwell time was longer for slow verbs than fast verbs for scenes in which there was no distractor, replicating the pattern of Experiment 7-2. This pattern was not observed for scenes with a distractor.

In order to further understand the time course of the differences in looks toward the destination, Figure 7-9 and 7-10 display the average proportion of samples with fixations on the target destination over a whole trial for scenes with and without a distractor. This figure shows how the pattern of looks toward the target destination was slightly delayed for slow verb sentences compared to fast verb sentences, and that looks then remained on the destination for longer, for scenes without a distractor only. Based on this pattern, I suggest that the differences in dwell time observed across the experiments reported here is because the simulation of the meaning of the sentence was *slower* for sentences describing slow motion than sentences describing fast motion, rather than being due to a reanalysis of the sentence meaning (i.e. looks towards the target destination for slow sentences did not fall and then rise again, but remained higher than those for fast sentences, falling at a slower rate).

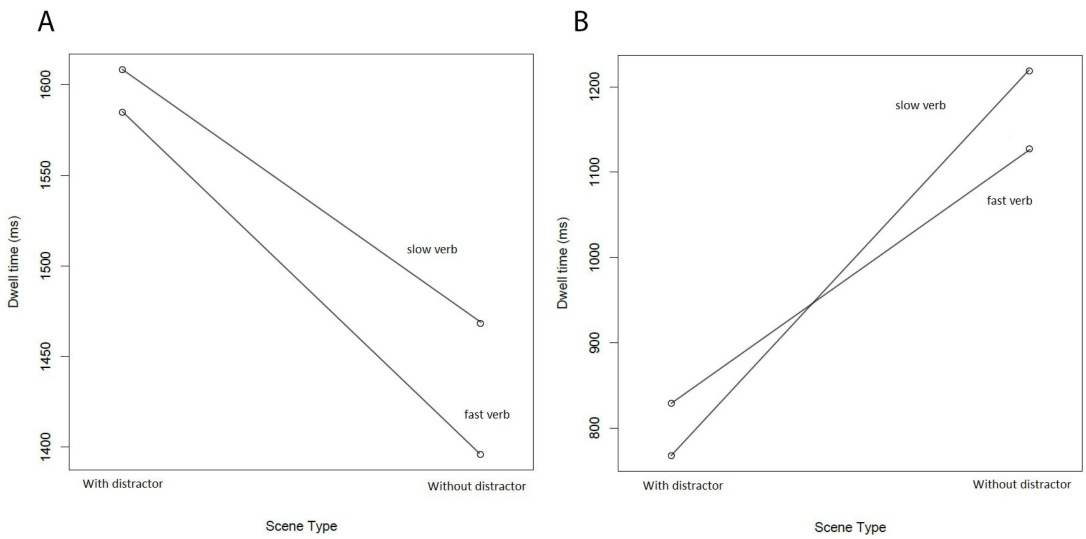

Figure 7-8. LME predicted mean dwell time on agent (A) and destination (B) for Experiment 7-3. Error bars reflect 1 standard error.

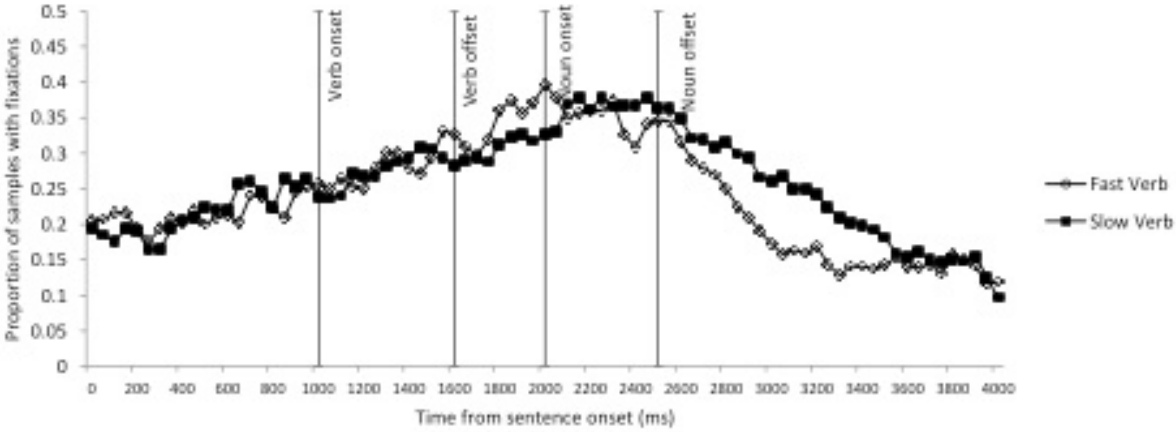

Figure 7-9. Proportion of samples with fixations towards the target destination for scenes without a distractor averaged over items in Experiment 7-3. Vertical lines denote average verb onset and offset, and noun onset and noun offset across all sentences.

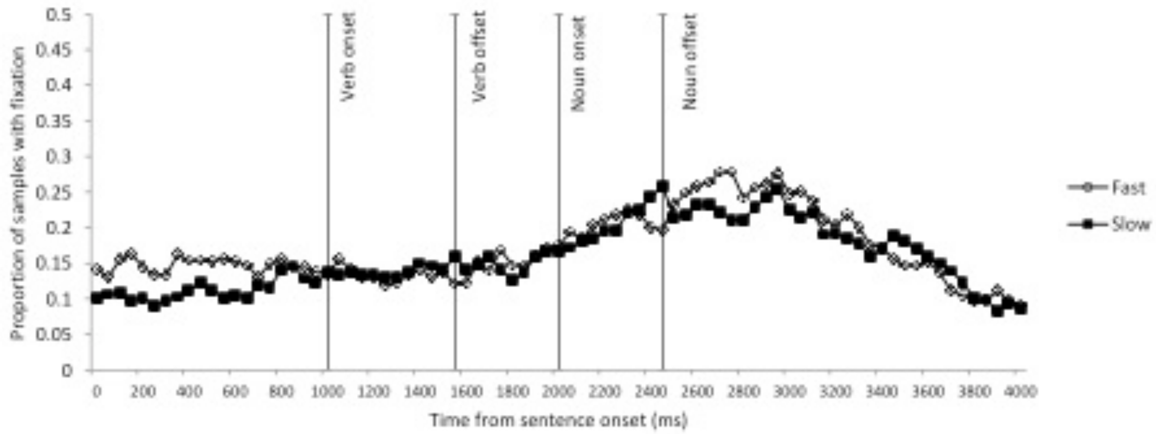

Figure 7-10. Proportion of samples with fixations towards the target destination for scenes with a distractor averaged over items in Experiment 7-3. Vertical lines denote average verb onset and offset, and noun onset and noun offset across all sentences.

7.3.3 Discussion

Thus, Experiment 7-3 has provided further evidence for the dynamic nature of simulations. When the visual scene was not ambiguous and contained only one target destination, looks to the destination were affected by the speed of the verb in the sentence. However, when there were two possible destinations, this pattern was not observed, suggesting that simulation was hindered by the ambiguity in the scene.

7.4 Experiment 7-4

In Experiments 7-1 and 7-2, using the fast and slow adverbs *quickly* and *slowly* did not affect looking behaviour towards the agent or destination in the visual scene. This could suggest that speeded adverbs do not sufficiently affect the speed of motion simulations, as speeded verbs do. This explanation seems unlikely because in comparison to speed verbs, which often include information other than speed such as manner of motion, *quickly* and *slowly* only describe speed. A reason for the null effects may be the repetition of *quickly* and *slowly*. After hearing them multiple times, their meaning may reduce in activation (e.g. Smith & Klein, 1990). Therefore, Experiment 7-4 continues to test the effect of speeded adverbs on mental simulations of motion by including a larger number of different speeded adverbs.

7.4.1 Method

7.4.1.1 Participants

Forty-four native English speakers with normal or corrected-to-normal vision (22 females, average age = 26.2 (*SD* = 10.9)) were recruited from the UCL Psychology subject pool and were paid for their participation.

7.4.1.2 Material

32 adverbs were chosen to be included in a norming study based on experimenter intuition and using an online dictionary and thesaurus. 10 participants (5 female, mean age = 25.1) were contacted by email and took part in the norming task online in their own time in the form of a Google survey. Two versions of the survey were created with a different random order of items. Participants viewed adverbs and were instructed to rate their speed with the following instructions:

"Please judge how fast you think the actions implied by the adverbs below are. Please imagine that all adverbs are used in the construction "the X adverb went to the Y" e.g. "The man angrily went to the car". Please rate an adverb as "7" if you think it is very fast, and please rate an adverb "1" if you think it is very slow. A score of "4" would mean motion that is neither fast nor slow. Please leave a question blank if you are unsure of the meaning of the adverb."

Participants viewed a horizontal 7-point scale with "Very slow" written on the left side and "Very fast" written on the right side. Responses were made using on the mouse.

Adverbs were classified as "fast" if both the mean and mode rating was greater than or equal to 5, and verbs were labelled as "slow" if both the mean and mode rating was less than or equal to 3. This led to 15 adverbs being classified as "slow" and 14 being classified as "fast". So that the 2 lists were equal, one slow adverb was removed. The chosen fast and slow adverbs were placed into sentences paired with the verb *went* e.g. *The gorilla lazily went to the pool.* Fast and slow adverbs are displayed in Table Appendix 1-4 and 1-5 and experimental sentences are displayed in Appendix section A2.2.4.

As in Experiment 7-1 and 7-2, the speaking rate was manipulated to be either slow or fast. Each experimental item therefore had four versions; a slow event with a slow speaking rate, a fast event with a fast speaking rate, a slow event with a fast speaking rate and a fast event with a slow speaking rate. Each participant heard only one version of each item. Thus there were four versions of the experiment with items allocated to each using a Latin Square design. Twenty-four filler sentences were created that did not describe motion (e.g. "*The gorilla glanced at the castle*").

Sentences were recorded by a speaker with an English accent in a soundproof room and spliced so that sentences with the same speaking rate were identical except for the adverb, with the resulting sentences sounding natural. Mean duration of sentences was 3936ms (*SD* = 177 ms) for slow speaking rate and 1749 ms (S*D* = 265 ms) for fast speaking rate.

Each experimental item was paired with a visual scene that included the agent and target destination of the sentence, as in Experiment 7-2.

7.4.1.3 Procedure

The experimental procedure was identical to Experiment 7-2.

7.4.2 Results

Data extraction proceeded in the same manner as the previous experiments. Analyses of response time and accuracy to comprehension questions can be found in section A3.4.

7.4.2.1 Dwell time

As in the previous experiments, the total dwell time across the whole trial on the agent and destination of the sentence was calculated.

7.4.2.1.1 Looks to the agent

For looks to the *agent* (Figure 7-11A), an LME controlling for word frequency and duration (in ms) of each adverb did not find a main effect of speed of adverb ($t < 1$) nor an interaction between adverb speed and scene type ($t < 1$). There was however, a main effect of speaking rate ($\beta = -.31$, $t = 3.9$, $p < 0.001$), with longer dwell time on the agent for slow speaking rate than fast speaking rate.

7.4.2.1.2 Looks to the destination

Average dwell times on the *destination* are shown in Figure 7-11B. Using an LME including frequency and duration (in ms) of each verb as predictors there was no main effect of speed of adverb (β = .01, t = 1.16, p = .25) but there was again a main effect speaking rate (β = -.54, t = 6.97, p < .001) with longer dwell time on the destination for slow speaking rate compared to fast speaking rate. There was also a marginally significant interaction between speed of adverb and speaking rate (β = -.07, t = 1.93, p =. 05). Looking at Figure 7-11B, dwell time was longer for slow adverbs than fast adverbs with fast speaking rate and dwell time was longer for fast adverbs than slow adverbs with slow speaking rate. There were no significant simple effects of adverb speed at either level of speaking rate (ps > 0.05).

In order to further understand the interaction in looks toward the destination, in Figures 7-12 and 7-13 I display the average proportion of samples with fixations on the target destination over a whole trial for sentences with a slow speaking rate and for sentences with a fast speaking rate. This figure shows that the proportion of looks toward the target destination was higher for fast adverb sentences than slow adverb sentences after the adverb offset (equivalent to verb onset) for sentences spoken slowly but not for sentences spoken quickly. For sentences spoken quickly, no clear patterns are visible. Based on this, I would like to argue that this is again evidence of simulation taking time to unfold and therefore, being present for sentences spoken slowly but not for sentences spoken quickly, as observed in Experiment 7-1 and Experiment 7-2.

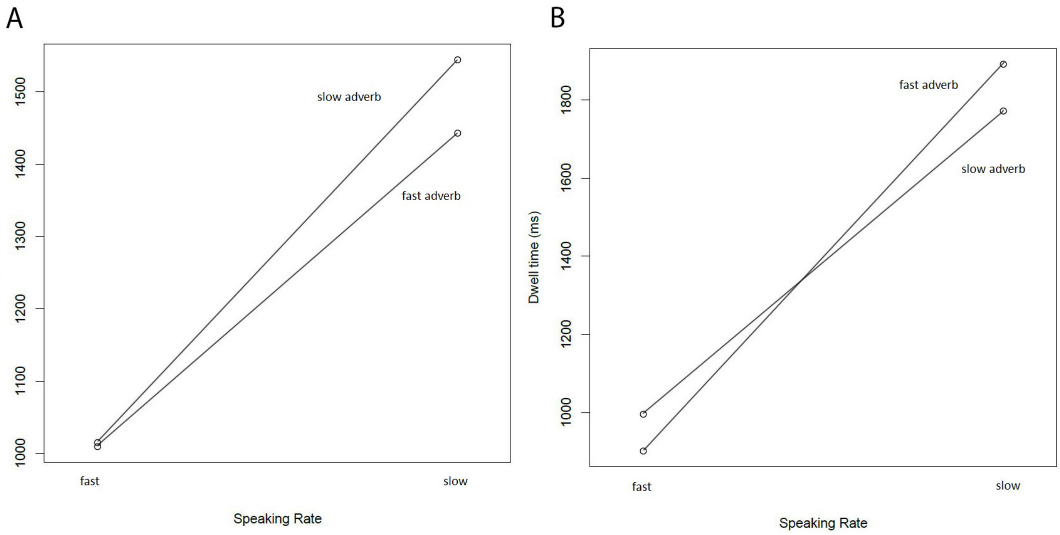

Figure 7-11. LME predicted mean dwell time on agent (A) and destination (B) in Experiment 7-4. Error bars reflect 1 standard error.

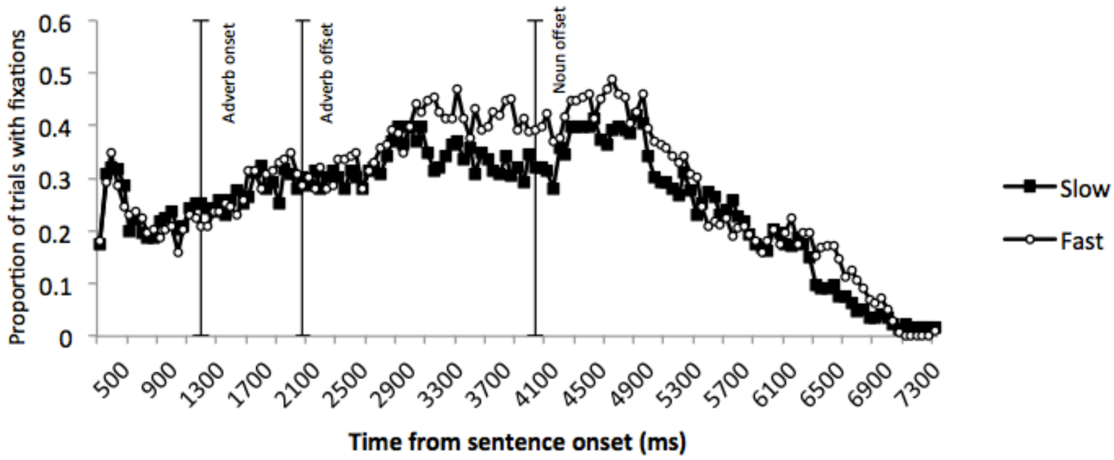

Figure 7-12. Proportion of looks to destination slow speaking rate Experiment 7-4. Vertical lines denote average adverb onset and offset and noun offset across all sentences.

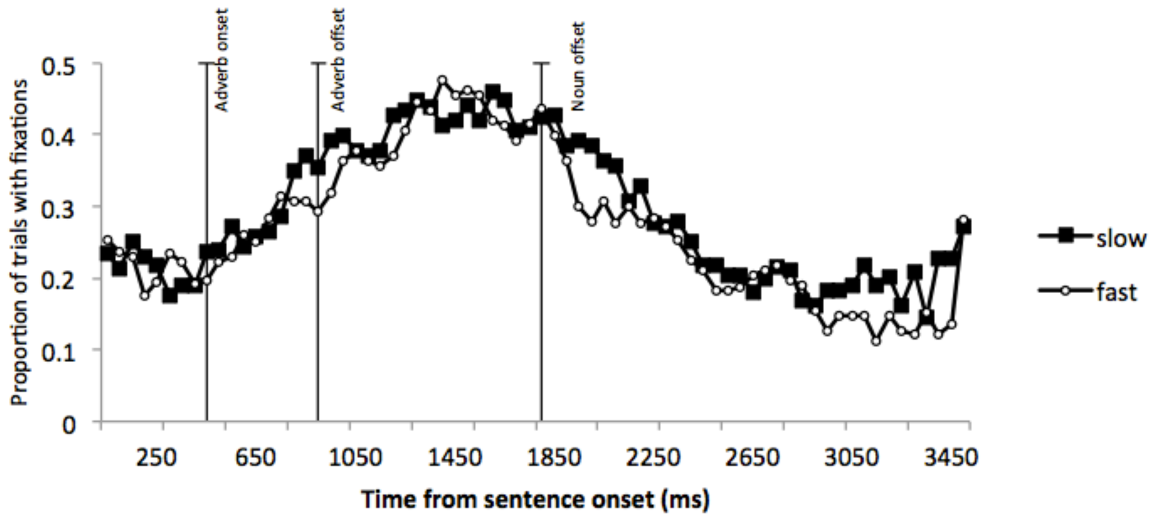

Figure 7-13. Proportion of looks to destination fast speaking rate Experiment 7-4. Vertical lines denote average adverb onset and offset and noun offset across all sentences.

7.4.3 Discussion

Participants spent more time looking towards the destination for sentences with fast adverbs compared to slow adverbs. This pattern is the opposite of what has been observed with verbs throughout Experiments 7-1 to 7-3. However it is in line with a very similar study (Lindsay, Scheepers & Kamide, 2013) that found greater looks to a target destination for fast verb sentences than slow verb sentences. They attributed this effect to mental simulation of fast events being completed more quickly, leading to earlier looks to the target destination and hence longer looking durations. However, in their study, experimental sentences emphasized the path of motion e.g. *The jeep will race along the* <u>*road*</u> *to the shop*. This directed participants' looks towards the path region, and did so for a longer duration for sentences with slow verbs compared to sentences with fast verbs, which subsequently lead to earlier looks to the destination for fast verbs. In the present case however, the sentences do not refer to the path and hence the path region received few looks. It is possible however, that less looks were directed to the destination for slow adverb sentences than fast adverbs sentences because they continued to look at other regions of the scene i.e.

the agent, whilst completing the simulation of motion. Although there is no significant interaction for looks to the agent, there is a visual trend for longer dwell time on the agent for sentences with slow adverbs compared to fast adverbs. Therefore, it is likely that when simulating slow sentences participants spent more time focusing on the agent, simulating it in motion for longer, but when simulating fast sentences, participants simulated the event more quickly, thereby looking towards the agent less and the destination more.

7.5 General Discussion

Using eye tracking, I found that when listening to sentences describing motion and viewing corresponding visual scenes, time spent looking at participating objects was affected by the interaction between speed of the verb/adverb of the sentence, speaking rate of the sentence and configuration of a corresponding visual scene. The data provide evidence that simulations develop in a manner consistent with the kinematics of real-world motion. Moreover, the results suggest that there is a link between simulation in language understanding and the low-level motor mechanisms that control eye-movements, and that these mechanisms are sensitive to fine-grained, dynamic motion information contained in a sentence. Mental simulations are not fixed but are flexible and built on the fly, interacting with relevant visual information when it is made available. The simulation observed, as evidenced by eye-movements, is the combination of linguistic information from the sentence, information extracted from the visual scene, and world knowledge, such as how motion events unfold. When this information is in conflict, or one source is unavailable or ambiguous (as the destination is in Experiment 7-1), the simulation does not take that into account and is limited to the other available information that is reliable. In the case of Experiment 7-1, since only the agent is known, the simulation focuses exclusively on the agent. The simulation is very different when, instead, the destination is known in which case, this latter is simulated. Note that in Experiment 7-3, the result of Experiment 7-1 was not replicated. This difference could be explained by the difference in task. In Experiment 7-3, participants were no longer required to click on the target destination, thus they did not have as much of an incentive to pay attention to the sentence and scene as in Experiment 7-1. Since the scenes with a distractor were temporarily ambiguous, comprehension of the sentence and scene was likely to be more difficult here, and hence participants may have processed them less efficiently. This is supported by the accuracy results for comprehension questions (Appendix section A3.3.) in which participants performed significantly worse in the 'with distractor' condition than the 'without distractor' condition. Importantly, in two experiments we have shown that when there is no ambiguity between the sentence meaning and the visual scene, there is a clear effect of the perceptual simulation of speed of motion as implied by verbs.

A difference in the pattern of interaction between sentence speed and speaking rate is observed between sentences that encode speed with a verb and sentences that encode speed with an adverb. Both verbs and adverbs find speed effects with slow speaking rate only, however for verb sentences, fast verbs lead to shorter dwell time on the destination than slow verbs, but for adverb sentences, fast adverbs lead to longer dwell time on the destination than slow adverbs. The effect with adverbs was not predicted, yet it is in line with results found elsewhere (Lindsay, Scheepers & Kamide, 2013). One major difference between the two sentence types in the present experiments is the timing of speed information. For verb sentences, speed is a component of the verb and is thus immediately tied to the motion event. For adverb sentences, speed is a component of the adverb and thus occurs earlier in the sentence, before the motion verb. The difference in timing of speed information may affect the way the motion simulation develops. When speed is a component of the verb, the simulation of motion is likely to already include the target destination because the motion event (of moving somewhere) is the dominant meaning of the verb (i.e. one simulates the meaning of a motion verb as movement to a specific location). Here the speed component affects the simulation at the target destination and hence looks here are longer for slow verbs than fast verbs because this simulation takes longer.

For adverbs however, the speed information occurs before the motion in the verb and thus is able to influence the simulation of motion more freely. Thus slow speed implied in an adverb leads to a slower simulation developing compared to fast adverbs, with the agent focused on for longer because it is in motion for longer. Conversely, fast speed implied in the adverb leads to a faster simulation than slow adverbs, which means than the target destination is reached earlier and hence looked at longer. To reiterate, this explanation suggests that verbs emphasize the motion event and so attract looks to the destination where the motion is completed, but by using an adverb first, the motion event can be modified by other factors implied by the adverb. Another possible explanation is linguistic focus (Taylor & Zwaan, 2008). By using an adverb, the focus of the sentence is likely to be on the manner of motion (i.e. fast or slow), because the purpose of an adverb is to modify an act. By using only a verb the focus instead is on the completion of the motion event (and hence the destination). This idea is also consistent with the results from Lindsay, Scheepers & Kamide (2013). In their sentences, the immediate focus of the motion verb was the path (e.g. *The jeep will race along the road to the shop*) and so differences in looks between fast and slow events were found at the path region and then the destination region. These results suggest that simulations also develop flexibly based on syntactic and grammatical information.

How are eye-movements engaged during sentence comprehension? The observed pattern of eye-movements could be explained as the mapping between one's mental representation of the world, which is dynamic and changeable, and incoming linguistic information (Altmann & Kamide, 2007). Thus, increased activation of elements in the developing simulation caused by the linguistic input can lead to a shift in covert attention to the corresponding elements in a visual scene, increasing the likelihood of overt eye-movements to their location (Altmann, 2011). In terms of the present results, the *speed* of motion described in the sentences affected the *speed* of the internally simulated event; thus, the duration of the activation of the elements in the sentence differed according to the speed of the verb/adverb and thus the time spent looking at those objects also differed. Spivey & Geng (2000) propose that the oculomotor system should respond to an activated visual representation irrespective of how it was generated (e.g. by visual perception, through language or by memory) because “After all, how could it know the difference?” (p. 240)

These results are also compatible with an action-based language theory (Glenberg & Gallese, 2011; see Chapter 1 section 1.5.1.). This theory proposes that when listening to sentences, speech controllers are activated as a form of covert imitation, which in turn activates corresponding action controllers for the meaning of the words. Following this, forward models are generated via predictors and the perceptual or motor consequences of the action controllers are anticipated. Predictors in this model correspond to simulators in embodied approaches (Barsalou, 1999a). In terms of the present data, activation of forward models for the heard sentences causes the eyes to move towards the objects that are anticipated, and they are looked at in a way consistent with the form of the predicted action.

One implication arising out of these results is that sentence comprehension in the conditions in which eye-movement simulation was not observed may be different to when simulation was observed. For example, when sentences are spoken quickly, or when the configuration of the visual scene makes matching between sentence and objects ambiguous, comprehension may be hindered. The present data does not allow this hypothesis to be tested. Additional research, such as directly manipulated eye-movements, would be invaluable to test these implications.

It is possible that the observed eye-movement patterns could be explained by a non-simulation account in which post-semantic imagistic representations develop from an amodal representation of the sentence meaning. Although I do not have evidence to rule out this view, the present interpretation is more favourable due to its parsimony: it postulates fewer representations. Moreover, looking at the time course of effects in Experiment 8-3 and 8-4 suggests that simulations develop quickly during online comprehension. Further investigations could test the functional role of the simulations evidenced by eye-movements by manipulating the eye-movement patterns in some way and assessing any comprehension difference

7.6 Chapter conclusion

The experiments in this chapter provide evidence for the online simulation of speed during spoken sentence comprehension using an experimental paradigm that allows a clear and natural observation of simulation: in comparison to the task employed in Chapter 6, measures of simulation do not require an explicit judgment about the sentence. Further, this work builds on the previous chapters by revealing the flexible and dynamic quality of mental simulation, showing that simulations are affected by factors other than the semantics of the sentence, such as speaking rate and concurrent visual information. This chapter also adds to the theoretical understanding of the processes linking language understanding and low-level visual mechanisms by showing that eye-movements are sensitive to subtle semantic differences like speed.

Chapter 8 Is speed processing in language affected by deficits in the motor system?

As described in the introduction of this thesis (Chapter 1 and 2), strong evidence for embodied theories comes from patient studies. Evidence from behavioural and fMRI studies only provide correlational support for the role of sensorimotor systems in comprehension, but not a causal role. Studies that use TMS to disrupt processing and then measure effects in comprehension show how these systems are causally involved in comprehension (e.g. Pulvermüller et al 2005; Tremblay, Sato & Small, 2012). More direct evidence for a necessary role of sensorimotor systems in comprehension comes from studies with neurological patients. In this chapter I assess the necessary role of speed simulation in comprehension of speed language by comparing performance on a number of tasks assessing comprehension of speed in language of patients with motor problems with healthy controls.

The majority of patient studies that investigate embodied theories assess comprehension of action language in patients who have motor difficulties. Bak et al. (2001) found that patients with motor neuron disease were significantly impaired in the production of verbs but not nouns, compared to healthy controls and patients with Alzheimer's disease. Further, Grossman et al. (2008) found that the degree of cortical atrophy in motor and premotor areas correlated with performance on action-verb judgments. Boulenger et al. (2008) examined action word comprehension in Parkinson's disease (PD) using a masked priming paradigm and found that priming effects for action verbs varied as a function of Levodopa uptake (medication that improves the motor impairment in PD). Further support from PD patients for a crucial role of the motor system in comprehension comes from Fernandino et al (2012), who removed the grammatical confound occurring when comparing verbs versus nouns by comparing PD patients and age-matched healthy controls on action verb and abstract verb processing. Compared to healthy controls, patients performed worse with action verbs than abstract verbs, reflecting a problem with action language rather than the grammatical category of verbs. Thus, action language depends on the integrity of the motor system. It should be noted however that these effects tend to be relatively small, and although differences do exist between patients and controls, patients can still comprehend action language to some extent. This suggests that although motor simulation may be a crucial component in comprehension of action language, comprehension is also supported by other systems including simulation in other modalities as well as other types of information such as statistical relations between words (Andrews et al., 2009).

A more definitive test for a functional role of sensorimotor systems in understanding speed language therefore would be to assess whether individuals with deficits in the sensorimotor processing of speed, for example from damage to the respective brain areas, also show impaired speed language comprehension. Patients with motor impairment, such as PD, provide an opportunity to test this hypothesis. PD is a neurodegenerative disease caused by a deficiency in the dopaminergic pathway leading to reduced activation in brain areas involved in motor planning and execution, including the primary motor cortex and the supplementary motor area (Fernandino et al., 2013). PD patients are characterized by a range of motor problems including bradykinesia (slowed movements) and rigidity. If the motor regions affected in PD are involved in understanding language about speed, then PD patients should show difficulties comprehending speed language compared to non-action language. Further, since PD patients have more difficulty moving quickly compared to slowly, they should be more impaired with language about fast actions compared to slow actions. Disembodied approaches would predict that comprehension of speed is not affected since the sensorimotor areas that are damaged are thought to have no functional role in language understanding.

I used three tasks that assess comprehension of speed in language at different depths of processing to investigate the conditions in which the motor system is involved in semantic processes for speed. Lexical decision (shown to be sensitive to a number of semantic variables (Yap et al., 2012)) with masked priming assesses motor contribution at an automatic, implicit level. In masked priming, the prime word is not consciously perceived. Thus, assessing priming with speed words assesses the automatic activation of speed simulation. If Parkinson's patients have impaired speed simulation at an automatic level, they should have reduced priming effects for speed verbs compared to abstract verbs (i.e. no difference between primed and unprimed targets). The controls however are expected to have faster responses to primed targets that unprimed targets for all verb types, due to preactivation of the target concept by the prime. Sentence comprehension assesses motor contribution at a level of implicit conscious activation. And semantic similarity judgments assess motor contribution during explicit semantic comparisons (Fernandino et al. 2013). Fernandino et al. (2013) found evidence for a causal role of the motor system in comprehension at all levels of processing, however since speed is a fine-grained and relatively abstract action feature it is not clear whether it would necessarily be activated at all levels or only when explicit semantic processing is required.

8.1 Method

8.1.1 Participants

Thirteen patients diagnosed with PD (average age 71.6, *SD* = 4.5, age range 64 - 78) were recruited from the Columbia Parkinson's support group and from the Palmetto Health Richmond hospital in Columbia, South Carolina. Table 8-1 presents patient details. Four patients were removed from all analyses for having low scores on the Montreal Cognitive Assessment (<21) (see description of test below). One patient did not complete the sentence sensibility task due to a computer error midway through the task and one patient was not included in the semantic similarity judgment analysis for performance being lower than 50% (although their accuracy in the other two tasks was high). Eleven healthy controls were recruited of a similar age (average 70.8 (*SD* = 8.6)), most of whom were partners of the PD patients. One control was removed for having a low MoCA score (<21) and one control did not complete the sentence sensibility task due to a computer crash. All participants were paid for their participation.

Table 8-1. Individual patient information for age (years), Montreal Cognitive Assessment (max=30), Unified Parkinson's Disease Scale (max = 32), Hoen-Yahr stage (max = 4).

Patient	Gender	Age	MoCA	UPDRS	Hoen-Yahr stage	Time since medication (minutes)	Years since diagnosis
P1	M	76	21	-	-	30	6
P2	M	76	25	17	2	75	24.4
P3	M	64	17	29	1	15	4.3
P4	F	65	18	26	3	90	3
P5	M	71	25	10	1	180	7.5
P6	M	66	29	31	2	320	3.8
P7	M	73	23	55	5	300	11
P8	F	74	27	19	1	300	11
P9	M	71	22	10	1	-	3.3
P10	F	74	20	41	3	330	-
P11	M	74	22	9	2	-	-
P12	M	69	25	22	2	355	0.4
P13	M	68	15	-	-	-	12

8.1.2 Material

Words to be used in the following experimental tasks were rated by participants of a similar age to the PD patients and matched on a number of psycholinguistic variables as described in Chapter 6, section 6.1.1.2.

Once the items sets had been selected, I ran a pilot study to check that response time and accuracy were equal across conditions for healthy subjects. Any condition that is already difficult for healthy subjects would be exaggerated with the PD group.14 healthy participants (average age 63.2, range 44-78) were recruited from the UCL Psychology Subject Pool and via email contact with members of the University of the Third Age in London (www.u3a.org.uk) and were paid for their participation. Any relevant results from the pilot study are discussed in reference to the particular word type below.

8.1.2.1 Lexical decision task (LDT)

The lexical decision task comprised three sets of experimental items: full body verbs matched with abstract verbs, hand/arm verbs matched with abstract verbs and fast, slow and abstract adverbs. Each set will be analysed separately. Sixteen fast & slow full body verbs and 16 abstract verbs were normed and matched e.g. *to whiz, to roam, to profess* (see Table Appendix 1-15 and 1-15), 11 fast and slow arm/hand action verbs and 11 abstract verbs were normed and matched e.g. *to yank, to brush, to know* (see Table Appendix 1-17 an 1-18), and 20 fast, slow and abstract adverbs were normed and matched e.g. *slowly, actively, hopefully* (see Table Appendix 1-20 and 1-21). The norming task and the matching procedure is described Chapter 4. Pseudo-words were generated from the English Lexicon Project (http://elexicon.wustl.edu) and matched with experimental words on length, number of orthographic neighbours and lexical decision accuracy (see Table Appendix 1-16, 1-19 and 1-22).

8.1.2.2 Sentence sensibility task (SST)

Sets of 13 abstract, fast and slow adverbs were matched as described in Chapter 6 (see Table Appendix 1-10 and 1-11). These adverbs were then placed into sentences matched in length and syntactic structure: 13 sentences with abstract adverbs and abstract actions **(**e.g. *Gwen knowingly allowed the breach*)**,** 13 sentences with fast and slow adverbs and abstract actions (e.g. *Mike quickly/carefully rated all the entries*) and

13 sentences with fast and slow adverbs and concrete actions (e.g. *Phil quickly/carefully lifted up the case*). Each participant saw all abstract adverb sentences and either a fast or slow version of each speeded abstract and concrete sentence, counterbalanced across trials (See Figure 8-1 for an example of three items counterbalanced across two participants). All sentences are displayed in Appendix section A2.1.3.

A.

Adverbs	Abstract action	Concrete action
Abstract	*Max usefully acquired all the new clients*	
Fast		*John speedily rolled up the sleeping bag.*
Slow	*Bob awkwardly thought over the business plan*	

B.

Adverbs	Abstract action	Concrete action
Abstract	*Max usefully acquired all the new clients*	
Fast	*Bob speedily thought over the business plan*	
Slow		*John awkwardly rolled up the sleeping bag.*

Figure 8-1. Example of the distribution of sentence conditions for two participants A and B.

8.1.2.3 Semantic Similarity Judgments (SSJ)

From the verbs that received more than three 'none' responses in the speed ratings, those with an average valence rating of 3 or less were considered 'negative' verbs, and those that scored an average valence rating greater than 6 were considered ‘positive’ verbs (following the methodology used in Bradley & Lang, 1999). The lists of positive, negative, fast and slow verbs were submitted to a matching program ‘Match’ (van Casteren & Davis, 2007) which matched 10 quadruplets of positive, negative, fast and slow verbs on number of letter, log frequency, number of orthographic neighbours, number of phonemes and number of syllables. The matched stimuli were then organized into ten triplets of either speed or valence to be used in the semantic similarity judgment task (see Table Appendix 1-23 and 1-24). Each word occurred in each of the three positions (target, match and foil).

After looking at the pilot data I decided that the speed trials were too difficult: mean accuracy for the fast and slow judgments were 74% and 67% respectively compared to 92% for both positive and negative emotion judgments. I also became aware of an existing hypothesis that would predict that Parkinson’s patients would also be impaired in emotion language because of their inability to fully experience facial expression (Mermillod, Vermuelen, Droit-Volet, Jalenques, Durif & Niedenthal, 2011). To address these issues I decided to change the speed trials to fast movement versus static movement and slow movement versus static movement (instead of fast vs. slow) to make judgments easier and add an additional set of trials as a control (word types where I would expect no impairment): thinking (e.g. *to ponder*) versus seeing words (e.g. *to watch*).

Thus, sixteen fast (e.g. *to run*), slow (e.g. *to shuffle*), positive (e.g. *to inspire*), negative (e.g. *to deceive*), thinking (e.g. *to ponder*) and seeing (e.g. *to watch*) verbs and two sets of verbs of no movement (e.g. *to stand*) were matched. Half of the fast and slow verbs were full body actions (e.g. *to run*) and half were hand/arm movements (e.g. *to grasp*). Items were then divided into four separate sets to serve as separate blocks within the experiment; positive and negative verbs; thinking and seeing verbs, fast actions and static actions and slow actions and static actions (see Table Appendix 1-25 and 1-26). The items were then divided into 32 triplets per block with each item serving as the target, match and foil once.

8.1.3 Procedure

Participants either came into the lab or were tested at Palmetto Richland Hospital, Columbia, South Carolina. All experimental testing was completed on a laptop running Windows. The whole session took around one hour but could be longer depending on the patients' need for breaks.

8.1.3.1 Unified Parkinson's Disease Scale

For those patients tested in the hospital (N = 11), the neurologist administered part III of the Unified Parkinson's Disease Scale (UPDRS), which assesses the patients' motor problems, to the patient. This testing took place either before of after the experimental session, depending on the availability of the neurologist.

8.1.3.2 Montreal Cognitive Assessment (MoCA)

Before the experimental session began all patients and controls were first administered the Montreal Cognitive Assessment (MoCA) to assess cognitive impairment. If participants scored too low on this assessment (cutoff score = 21 (Dalrymple-Alford et al., 2010)) then they were excluded from the analysis, as this would suggest that they had PD dementia. The MoCA has been shown to be more sensitive than other cognitive assessments such as the Mini Mental State Examination (MMSE), particularly for assessing milder cognitive deficits in PD (Hoops, Nazem, Siderowf, Duda, Xie, Stern & Weintraub, 2009), and as good as or better than PD-focused cognitive instruments (Dalrymple-Alford et al., 2010) in discriminating between patients with normal cognitive functioning and patients with mild cognitive impairment (MCI).

The MoCA comprises seven sections assessing visuospatial/executive skills, naming, delayed recall, attention, language, abstraction and orientation. The test is scored out of 30, with typical cutoffs for MCI at <26 and dementia at <21. The test takes around 10 minutes to administer.

8.1.3.3 Language comprehension tasks

All comprehension tasks were administered on a laptop running E-prime software in one session, with short breaks between each task. For all tasks, participants responded using two coloured Ablenet Jelly Bean buttons (www.ablenetinc.com). Responding with the Jelly Bean buttons is easier than other types of button response (e.g. keyboard press) because they are much larger. The red button was placed on the left and the green button was placed on the right (serving as "no" and "yes" responses respectively for the LDT and SST). Participants were instructed to respond only with their dominant hand and to rest it between the two buttons between responses. This meant that the average speed of response was the same for 'yes' and 'no' responses. The LDT and SST were administered either first or second (counterbalanced across participants). The SSJ was always administered last since this task required explicit judgments about the word types of interest, which could affect performance in the LDT and SST if participants were aware of them.

8.1.3.3.1 Lexical Decision Task

Each lexical decision trial began with a fixation cross in the centre of the screen for 500ms, followed by eight hashmarks for 100ms, then the prime stimulus for 50ms, a further 100ms of eight hashmarks and finally the target word (see Figure 8-2). The target word remained onscreen until the participant responded or until the trial timed out (after 4000ms). Each verb or pseudo-verb was presented with the word "to" to the left and each adverb or pseudo-adverb was presented alone. The prime was either the same word in capitalized form so that it was visually distinct from the target word, or a string of capitalized consonants of the same length of the word, counterbalanced across participants. Participants were instructed to press the green button if the item was a real English word, and to press the red button if it was not. The letters “N” and “Y” were presented under each item with a blue box appearing around the response made to indicate that the response had been registered. Participants first completed six practice trials with three real words and three non-words, with feedback on each trial. The task was divided into two blocks with the order counterbalanced: one block of verbs and one block of adverbs. The task took around 15 minutes to complete.

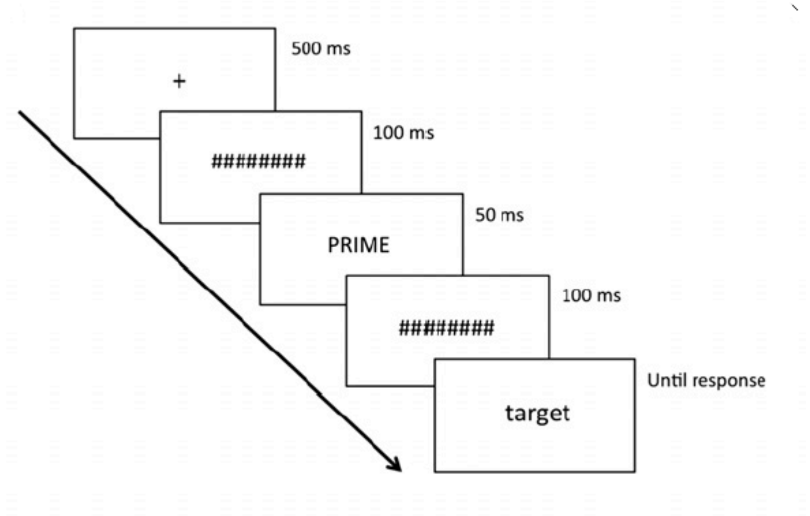

Figure 8-2. Procedure for lexical decision task. Figure taken from Fernandino et al/ 2013.

8.1.3.3.2 Sentence Sensibility Task

Each trial began with a fixation cross in the centre of the screen for 500ms followed by presentation of the full sentence in written form. The sentence remained on screen until the participant had responded or until the trial had timed-out (after 5000ms). Participants were instructed to press the green button if the sentence made sense or the red button if it did not. They were given examples of sentences that did and did not make sense in the instructions and the experimenter confirmed that they understood the task. The letters “N” and “Y” were presented under each sentence with a blue box appearing around the response made to indicate that the response had been registered.

Participants first completed six practice trials with three sentences that made sense and three that did not, with feedback on each trial. The task took around 10 minutes to complete.

8.1.3.3.3 Semantic Similarity Judgment

For each trial, three verbs were presented in a triangular arrangement. Each verb was presented with the word “to” to its left. Participants were instructed to indicate which of the two bottom words was most similar in meaning to the top and to press the right button for the word on the right and the left button for the word on the left. The position of the matching verb was counterbalanced across subjects. Since the way that items could be similar was so diverse, the items were divided into four blocks of judgments (movement vs. static action (with slow verbs), movement vs. static action (with fast verbs), thinking vs. seeing verbs and positive vs. negative verbs) with specific instructions about the type of judgment to be made at the beginning of each block. The experimenter went through these instructions carefully with each participant to ensure that they knew what type of judgment they were making. The triangular arrangement stayed on screen until the participant had responded or the trial had timed out (after 5000ms). A blue square appeared around a word when a response had been made to show that the response had been registered. Participants first completed six practice trials with words that denoted facial expressions (e.g. *to grin*) versus words that denoted vocalizations (e.g. *to yell*) with feedback given on each trial. The task took around 10 minutes to complete.

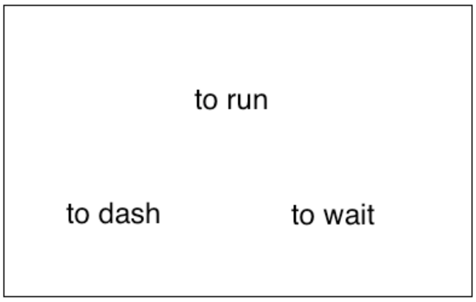

Figure 8-3. Example trial for semantic similarity judgments. Participants had to choose which of the bottom two words matched the top word according to a specific dimension (in this case movement versus static action).

8.2 Results

8.2.1 Lexical decision task

Items and their matched items were removed from analysis if their accuracy in control participants was less than 70%. Trials with response time greater than 3000ms, less than 250ms or outside 1.5*SD*[11] of a participant's mean response time were removed (< 10%). Average accuracy and response time, based on correct responses only, for each condition was calculated for each participant (collapsing across both primed and unprimed trials). Priming scores were calculated for each condition for each participant by subtracting their average response time for primed trials from their average response time for unprimed trials.

Data was initially explored with a 3 (word type) X 2 (group) mixed ANOVA, with word type a within subjects variable and group a between. To directly test the predictions of the chapter that PD patients will be impaired with fast versus slow words and with fast and slow words compared with abstract words, and controls will not, I also conducted independent t-tests between PD patients and controls on net response time, net accuracy and net priming (abstract – fast, abstract – slow, abstract –

[11] A cutoff value of 1.5*SD* provides more power to detect differences in data with a large amount of variance (Ratcliff, 1993).

speed and fast - slow). Using independent t-tests allows greater power to detect a priori predictions (Fernandino et al. 2013).

8.2.1.1 Adverbs

Here I contrast accuracy, response time and priming scores for abstract adverbs (e.g. *hopefully*), fast adverbs (e.g. *actively*) and slow adverbs (e.g. *slowly*) between PD patients and controls. If comprehension of speed words at all levels of processing requires simulation of speeded action I would expect performance to be worse (lower accuracy, longer response time or reduced priming) in patients but not controls for fast adverbs compared to slow adverbs, and between speed adverbs (fast and slow) compared to abstract adverbs. The predicted effect would be shown in an interaction between word type (abstract, fast and slow) and group (PD vs. controls) in accuracy, response time or priming scores or as an effect of group in net accuracy, net response time or net priming scores.

8.2.1.1.1 Accuracy

Average accuracy is displayed in Figure 8-4. There was no difference in accuracy for adverbs between word types (F (2, 34) = 1.12, p = .34, η^2_p = .06) or group (F (1, 17) = 1.12, p = .31, η^2_p = .06) and no interaction (F (2, 34) = 1.12, p = .34, η^2_p = .06).

There was no difference in net accuracy between PD patients and controls for any of the comparisons (t (17) = 1.06, p =. 31, d = .49). Thus there was no evidence for a difference between patients and controls in accuracy scores to adverbs.

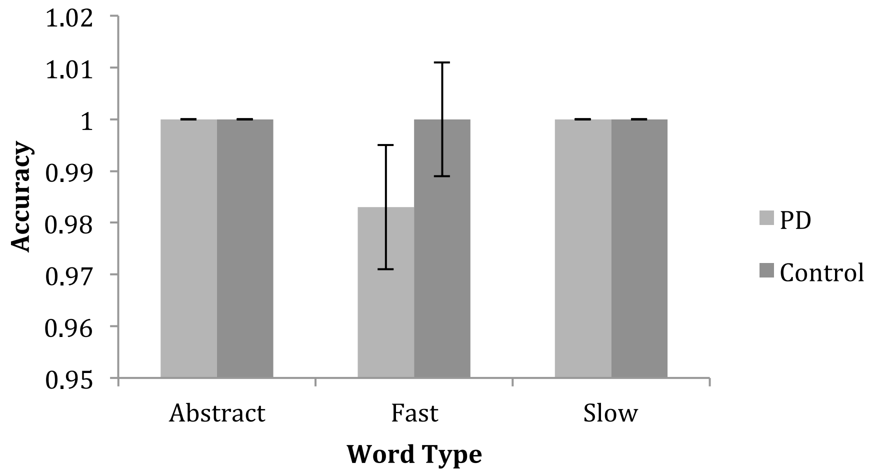

Figure 8-4. Average accuracy to adverbs in lexical decision task. Error bars reflect 1 standard error.

8.2.1.1.2 Response time

Average response time is displayed in Figure 8-5. PD patients were significantly slower than controls (F (1, 17) = 6.09, p = .025, η^2_p = .26) but there were no differences across word types (F < 1) and no interaction (F (2, 34) = 2.29, p =. 12, η^2_p = .12).

There was however a significant difference in net response time between PD patients and controls for the difference between abstract and fast adverbs (t (17) = 2.66, p = .02, d = 1.22) and abstract and speed adverbs combined (t (17) = 2.24, p = .04, d = 1.03), but not between abstract and slow adverbs (t (17) = 1, p = .33, d = .46) or between fast and slow adverbs (t < 1). Response time was slower for abstract words compared to fast and fast and slow combined in PD patients but not controls. This result is opposite to the hypotheses in this chapter.

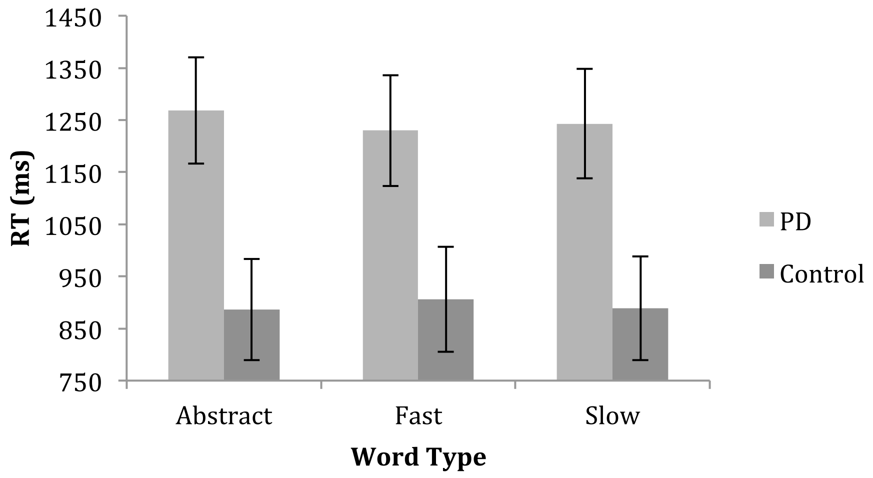

Figure 8-5. Average response time to adverbs in lexical decision task. Error bars reflect 1 standard error.

8.2.1.1.3 Priming

Average priming scores are displayed in Figure 8-6.There was a marginal difference in priming scores across word types (F (2, 34) = 3.17, p = .06, η^2_p = .16) but not across groups (F (1, 17) = 1.85, p = .19, η^2_p = .1) and there was no interaction (F (2, 34) = 1.48, p = .24, η^2_p = .08). Priming scores were lower for abstract adverbs than fast adverbs (F (1, 17) = 7.91, p = .012, η^2_p = .32) and marginally lower than slow adverbs (F (1, 17) = 3.92, p = .06, η^2_p = .19) but there was no difference between fast and slow adverbs ($F < 1$).

There was a marginal difference in net priming between PD patients and controls with abstract adverbs having lower priming scores compared to fast (t (17) = 1.74, p = .1, d = .8) and speed combined (t (17) = 2.02, p = .06, d = .9) in PD but not controls. This suggests that PD patients have problems processing abstract adverbs compared to fast and slow adverbs but controls do not, which was not predicted. There was no difference between PD patients and controls in net priming between fast and slow adverbs ($t < 1$).

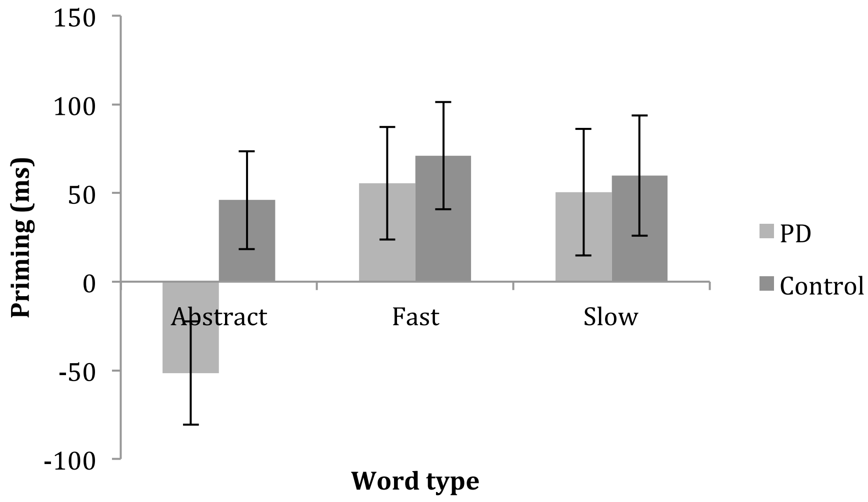

Figure 8-6. Average priming effect for adverbs in lexical decision task. Error bars reflect 1 standard error.

8.2.1.2 Full Body Verbs

Here I contrast accuracy, response time and priming scores for abstract verbs (e.g. *to profess*), fast full-body verbs (e.g. *to whiz*) and slow full-body verbs (e.g. *to roam*) between PD patients and controls. To reiterate the main hypotheses, if comprehension of speed words at all levels of processing requires simulation of speeded action I would expect performance to be worse (lower accuracy, longer response time or reduced priming) in patients but not controls for fast verbs compared to slow verbs, and between speed verbs (fast and slow) compared to abstract verbs. The predicted effect would be shown in an interaction between word type (abstract, fast and slow) and group (PD vs. controls) in accuracy, response time or priming scores or as an effect of group in net accuracy, net response time or net priming scores.

Two full body verbs (*to plod* and *to flit*) and their matched items were removed from analysis for having low accuracy in controls (70%).

8.2.1.2.1 Accuracy

Average accuracy is displayed in Figure 8-7. There was a significant difference between word type (F (2, 34) = 4.15, p = .02, η^2_p = .2) with accuracy for abstract verbs lower than accuracy for fast full body verbs (F (1, 17) = 5.85, p = .03, η^2_p = .26) but not slow fully body verbs (F (1, 17) = 2.97, p = .1, η^2_p = .15) and no difference between fast and slow full body verbs (F (1, 17) = 2, p = .18, η^2_p = .11). There was no difference in accuracy across groups (F<1) and no interaction (F<1).

There was no difference in net accuracy between PD patients and controls for any of the contrasts (ps > .05)

Thus there was no support for my hypotheses in accuracy for full-body speed verbs.

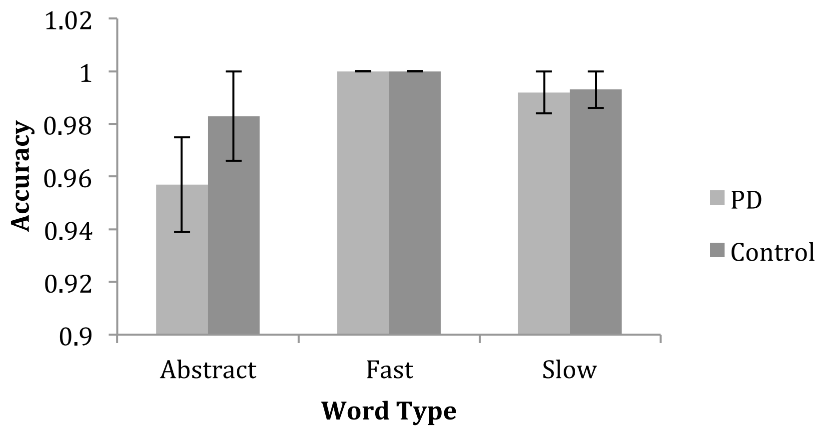

Figure 8-7. Average accuracy for full-body verbs in lexical decision task. Error bars reflect 1 standard error.

8.2.1.2.2 Response time

Average response tine is displayed in Figure 8-8. There was a significant difference across word types (F (2, 34) = 4.46, p = .019, η^2_p = .21) with responses slower to abstract verbs than fast full body verb (F (1, 17) = 7.2, p = .02, η^2_p = .3) but there was no difference between abstract verbs and slow full body verbs (F (1, 17) = 2.05, p =

.17, η^2_p = .11) or between fast full body verbs and slow full body verbs (F (1, 17) = 2.86, p =. 11, η^2_p = .14). Responses for PD patients were significantly slower than responses for controls (F (1, 17) = 8.98, p < .01, η^2_p = .35). There was no interaction (F < 1).

There was no difference in net response time between PD patients and controls between any of the comparisons (ps> .05)

Thus there was no support for my hypotheses in response time for full-body speed verbs.

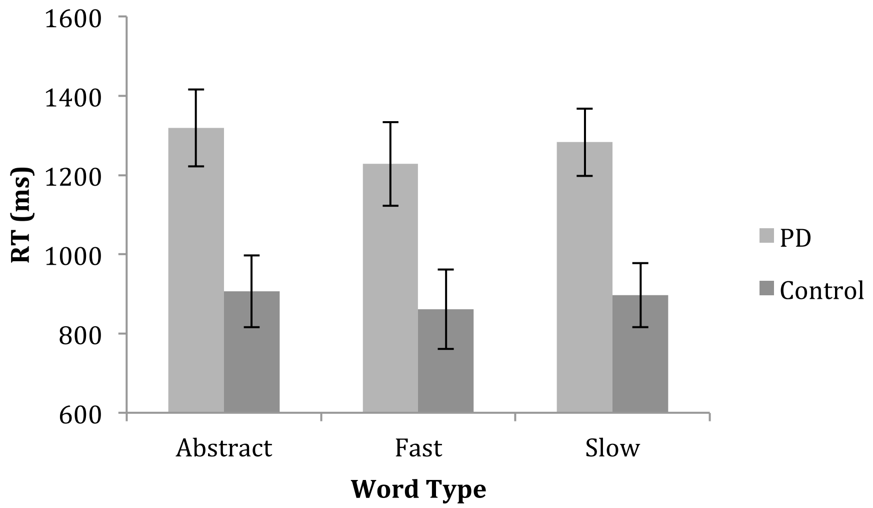

Figure 8-8. Average response time for full-body verbs in lexical decision task. Error bars reflect 1 standard error.

8.2.1.2.3 Priming

Average priming scores are displayed in Figure 8-8. There was a significant difference between groups (F (1, 19) = 5.56, p = .03, η^2_p = .25) with overall less priming in PD than control. There was no difference in priming scores across word types (F < 1) and no interaction (F < 1). However there was a numerical trend for reduced priming in both fast and slow full body verbs but not abstract verbs for PD patients but not controls.

There was no difference in net priming between PD patients and controls for any of the comparisons.

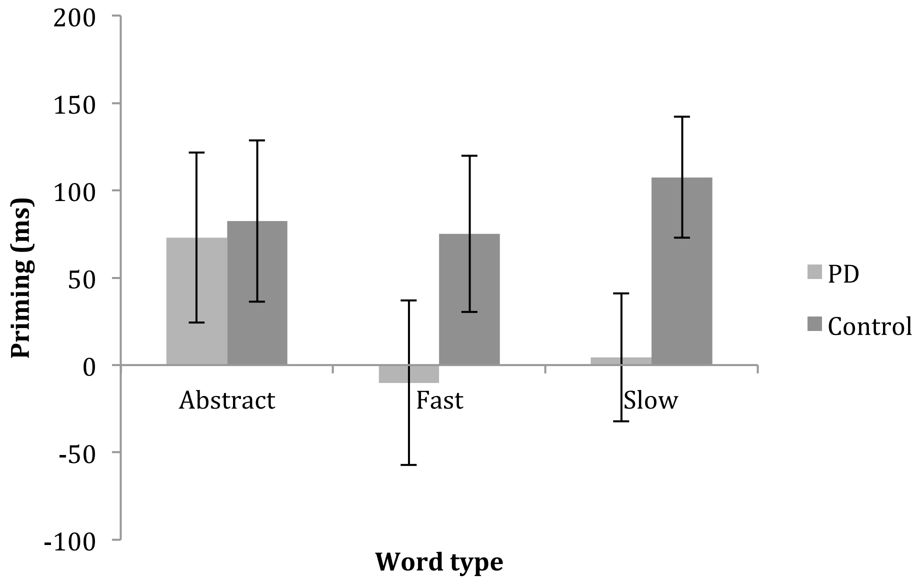

Figure 8-9. Average priming effect for full-body verbs in lexical decision task. Error bars reflect 1 standard error.

8.2.1.3 Hand/arm verbs

Here I contrast accuracy, response time and priming scores for abstract verbs (e.g. *to know*), fast hand/arm verbs (e.g. *to yank*) and slow hand/arm verbs (e.g. *to brush*) between PD patients and controls. Again, if comprehension of speed words at all levels of processing requires simulation of speeded action I would expect performance to be worse (lower accuracy, longer response time or reduced priming) in patients but not controls for fast verbs compared to slow verbs, and between speed verbs (fast and slow) compared to abstract verbs. The predicted effect would be shown in an interaction between word type (abstract, fast and slow) and group (PD vs. controls) in accuracy, response time or priming scores or as an effect of group in net accuracy, net response time or net priming scores.

8.2.1.3.1 Accuracy

Average accuracy is displayed in Figure 8-10. there was a significant interaction between word type and group (F (2, 34) = 4.29, p = .02, η^2_p = .2). Accuracy for abstract verbs was marginally lower than accuracy for fast and slow hand/arm verbs for PD patients (t (8) = 2, p = .08, d = .7) but not for controls (t (9) = 1, p = .34, d = .32). There was no overall difference in accuracy between word types (F (2, 34) = 2.44, p = .1, η^2_p = .13) or groups (F (1, 17) = 1.5, p=. 24, η^2_p = .08).

The interaction was supported with independent t-tests on net accuracy. There was a significant difference in net accuracy between PD patients and controls for the difference between abstract and fast hand/arm verbs (t (17) = 2.12, p = .05, d = .97), abstract and slow full hand/arm verbs (t (17) = 2.28, p = .04, d = 1.05) and abstract and speed verbs combined (t (17) = 2.31, p = .0, d = 1.06). There was no difference in net accuracy between fast and slow hand/arm verbs between PD patients and controls ($t < 1$).

Thus contrary to predictions, PD patients performed worse with abstract verbs than speeded verbs describing hand/arm actions.

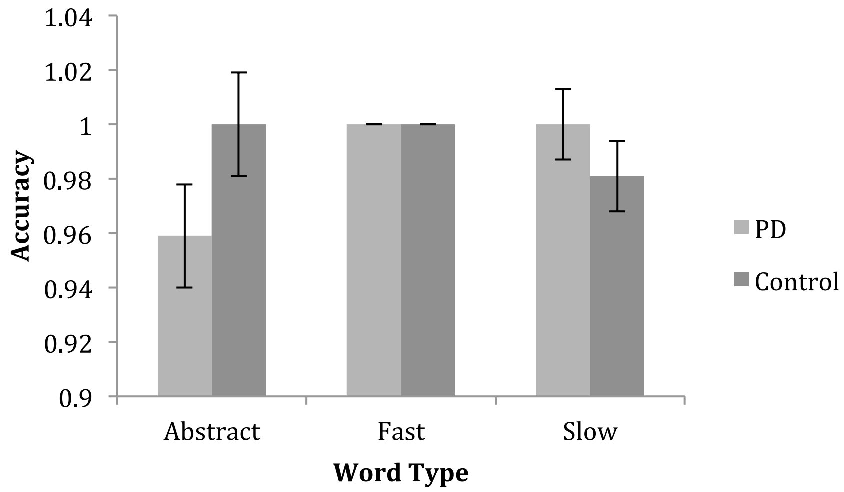

Figure 8-10. Average accuracy for hand/arm verbs in lexical decision task. Error bars reflect 1 standard error.

8.2.1.3.2 Response time

Average response time is displayed in Figure 8-11. Responses in the PD group were slower than the control group (F (1, 17) = 6.81, p = .02, η^2_p = .29) but there were no differences in response time between word types (F (2, 34) = 1.45, p = .25, η^2_p = .08) and no interaction (F (2, 34) = 1.27, p = .29, η^2_p = .07).

There was no difference in net response time between PD patients and controls for any of the comparisons (ps> .05).

Thus there was no evidence in support of the hypotheses in response time to hand/arm verbs.

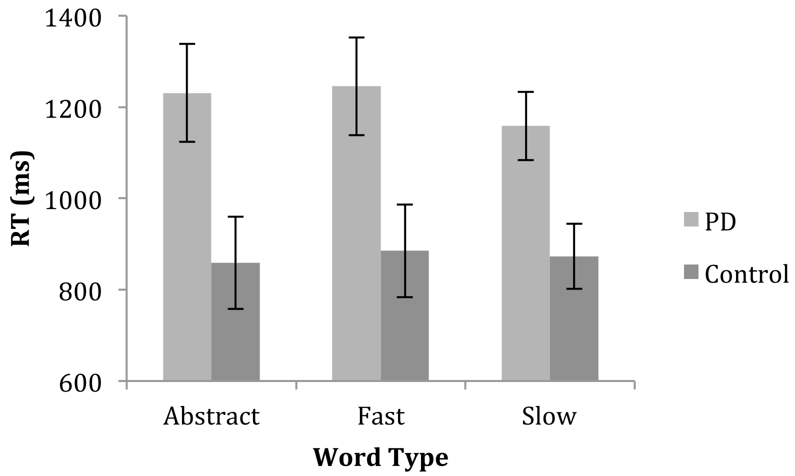

Figure 8-11. Average response time for hand/arm verbs in lexical decision task. Error bars reflect 1 standard error.

8.2.1.3.3 Priming

Average priming scores are displayed in Figure 8-12. There was no effect of word type (F (2, 34) = 1.62, p = .21, η^2_p = .09) or group and no interaction (F<1). There was no difference in net priming between patients and controls for any of the comparisons (ts <1).

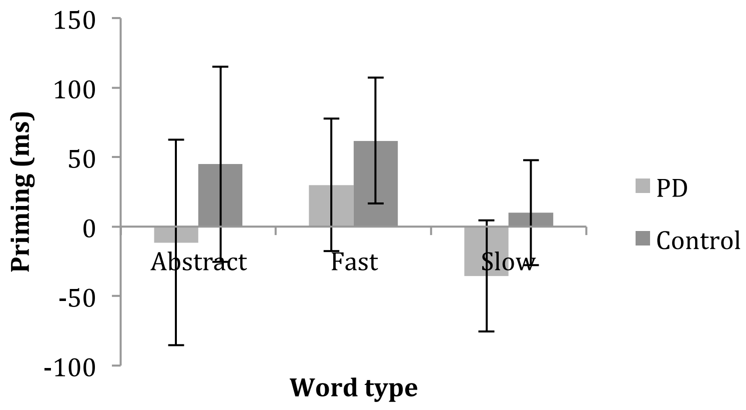

Figure 8-12. Average priming effect for hand/arm verbs in lexical decision task. Error bars reflect 1 standard error.

8.2.1.4 Summary: Lexical Decision

In terms of the predictions of this chapter, there were no differences between PD patients and controls for the difference between responses to fast and slow verbs and adverbs. For full body verbs, there was a trend for reduced priming for fast and slow verbs compared to abstract verbs, for PD patients only, suggesting that processing of action words is impaired compared to abstract words, as shown in previous work (e.g. Fernandino et al, 2013). However, speed does not appear to be affected at this level.

Contrary to predictions, PD patients but not controls showed less priming for abstract adverbs compared to fast and slow adverbs and lower accuracy to abstract verbs compared to fast and slow hand/arm verbs. Thus, abstract verbs appear to be problematic for PD patients. Possible reasons for these difficulties are discussed in the General Discussion.

8.2.2 Sentence sensibility judgments

Sentences and their matched sentences were removed if accuracy in control participants was less than 70% (two abstract sentences with abstract adverbs and one concrete sentences with a slow adverb). Trials with response time greater than 5000ms, less than 250ms or outside 1.5*SD* of a participant's mean were removed (<12%). Average accuracy and response time, based on correct responses only, for each condition was calculated for each participant.

For abstract sentences, data was initially explored with a 3 (sentence type) X 2 (group) mixed ANOVA, with sentence type a within subjects variable and group a between. To directly test the prediction that PD patients will be impaired with fast sentences the most, and with fast and slow sentences compared with abstract words, and controls will not, I also conducted independent t-tests on net response time and net accuracy (abstract – fast, abstract – slow, abstract – speed, fast – slow) for greater power (Fernandino et al., 2013).

For concrete sentences, data was analysed with a 2 (sentence type) X 2 (group) mixed ANOVA, with sentence type a within subjects variable and group a between. Independent t-tests were also conducted on net accuracy and net response time (fast – slow).

8.2.2.1 Abstract sentences

Here I contrast accuracy and response time to sentences describing abstract actions with either a fast, slow or abstract adverb, between PD patients and controls. If comprehension of speed requires simulation of speeded action I would expect performance to be worse (lower accuracy or longer response time) in patients but not controls for sentences with fast adverbs compared to sentences with slow adverbs, and between sentences with speed adverbs (fast and slow) compared to sentences with abstract adverbs. The predicted effect would be shown in an interaction between adverb type (abstract, fast and slow) and group (PD vs. controls) in accuracy or response time or as an effect of group in net accuracy or net response time.

8.2.2.1.1 Accuracy

Average accuracy is displayed in Figure 8-13. There was no evidence of impairment in comprehension of speed for PD patients in accuracy scores for abstract sentences. There was no difference in accuracy between adverb type (F<1) or group (F<1) and no interaction (F (2, 36) = 1.01, p = .37, η^2_p = .05). There was no difference in net accuracy between PD patients and controls for any of the comparisons.

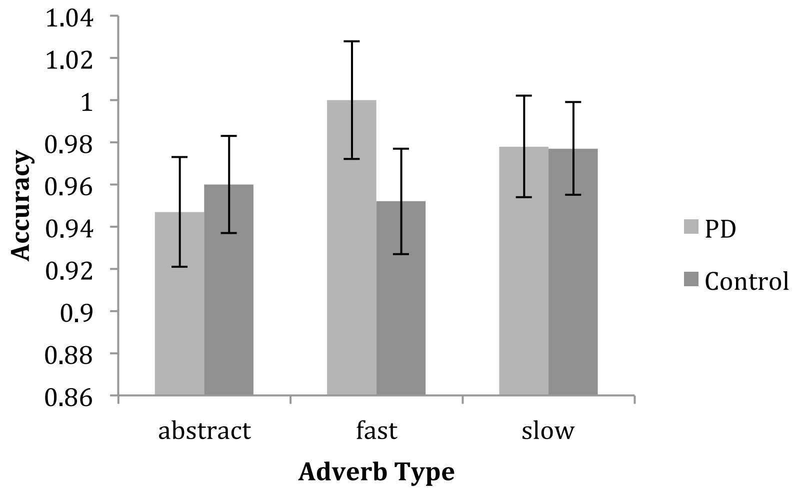

Figure 8-13. Average accuracy for abstract sentences in sentence sensibility task. Error bars reflect 1 standard error.

8.2.2.1.2 Response time

Average response time is displayed in Figure 8-14.Responses were slower in the PD group compared to the control group (F (1, 18) = 5.77, p = .03, η^2_p = .24) and there was a marginal difference across adverb types (F (2, 36) = 2.97, p = .06, η^2_p = .14). There was also a significant interaction between adverb type and group (F (2, 36) = 3.38, p = .05, η^2_p = .19). In line with predictions, the PD group responded to sentences with fast adverbs more slowly than they responded to sentences with slow adverbs (t (8) = 2.53, p = .04, d = .84) and marginally slower than sentences with abstract adverbs (t (8) = 2.06, p = .07, d = .69), but there was no difference between sentences with abstract and slow adverbs (t (8) = 1.15, p = .28, d = .38). For controls there was no difference between sentences with abstract adverbs and sentences with fast adverbs (t (10) = 1.08, p = .31, d = .34), nor between sentences with fast adverbs and sentences with slow adverbs (t < 1). However, there was a marginal difference between sentences with abstract adverbs and sentences with slow adverbs (t (10) = 1.88, p = .09, d = .59), with response to slow adverbs sentences being longer than response to abstract adverb sentences. This marginal difference may reflect simulation of slow speed in controls.

In net response time there was a significant difference between PD patients and controls between fast and slow sentences (t (18) = 2.23, p = .04, d = 1). However there was no difference in net response time between PD patients and controls between abstract and fast sentences ($t < 1$) nor abstract and speed sentences combined ($t < 1$) but there was a marginal difference between groups for abstract and slow sentences (t (18) = 1.85, p = .08, d = .83) with response faster to slow sentences than abstract sentences in PD patients, but the opposite pattern for controls. There were no differences between adverb types however for control participants ($p > .1$).

Thus here I provide evidence that PD patients are slower to comprehend sentences describing fast speed than sentences describing slow and abstract versions of the same action, in line with predictions.

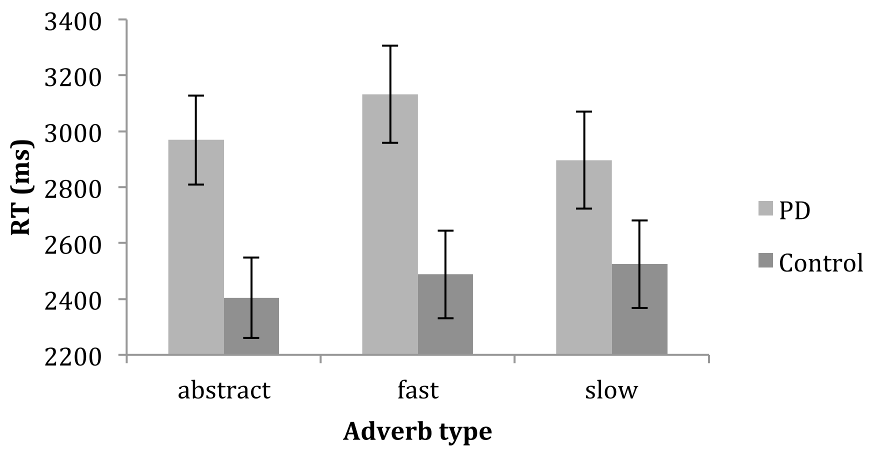

Figure 8-14. Average response time for abstract sentences in sentence sensibility task. Error bars reflect 1 standard error

8.2.2.2 Concrete sentences

Here I contrast accuracy and response time to sentences describing concrete actions with either a fast or slow adverb, between PD patients and controls. Again, if comprehension of speed requires simulation of speeded action I would expect performance to be worse (lower accuracy or longer response time) in patients but not controls for sentences with fast adverbs compared to sentences with slow adverbs. The predicted effect would be shown in an interaction between adverb type (fast and slow) and group (PD vs. controls) in accuracy or response time or as an effect of group in net accuracy or net response time.

8.2.2.2.1 Accuracy

Average accuracy is displayed in Figure 8-15. There was no evidence for impairment in fast versus slow comprehension in PD patients or controls. PD patients were marginally less accurate than control patients (F (1, 18) = 3.91, p = .06, η^2_p = .18) but there was no difference in accuracy between adverb type (F (1, 18) = 1.38, p = .26, η^2_p = .07) and no interaction (F < 1). There was no difference in net accuracy between PD patients and controls (t < 1).

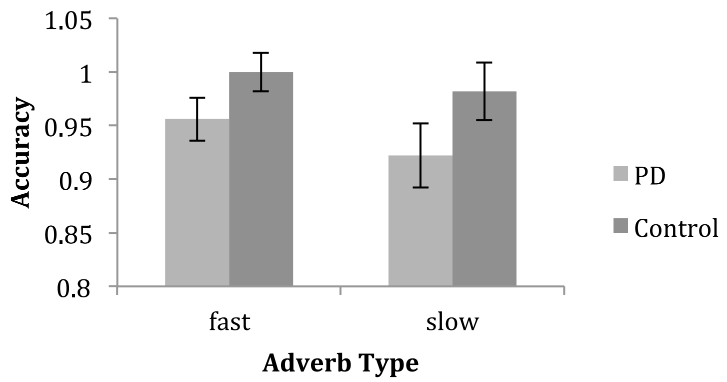

Figure 8-15. Average accuracy for concrete sentences in sentence sensibility task. Error bars reflect 1 standard error.

8.2.2.2.2 Response time

Average response time is displayed in Figure 8-16. PD patients were significantly slower than control participants (F (1, 18) = 6.49, p = .02, η^2_p = .27) but there was no difference in response time across adverb type (F<1) and no interaction (F < 1). There was no difference in net response time between PD patients and controls (t < 1). Thus there was no evidence in support of my hypotheses in response time.

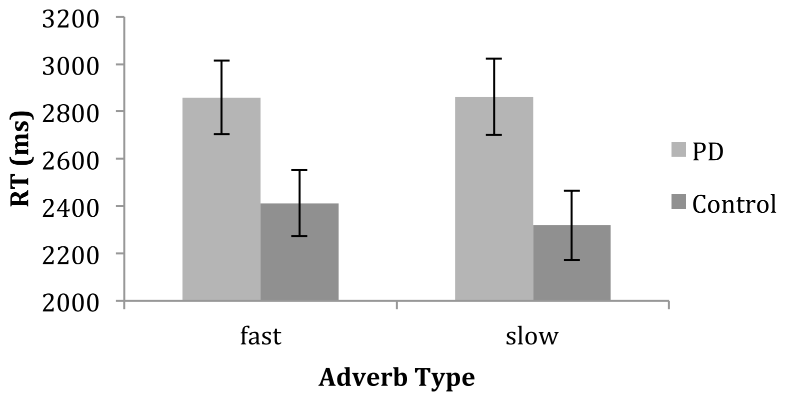

Figure 8-16. Average response time for concrete sentences in sentence sensibility task. Error bars reflect 1 standard error.

8.2.2.3 Summary SSTs

In line with predictions, PD patients were slower comprehending fast sentences compared to abstract and slow sentences, but only when the sentence described an abstract action and not a concrete action. This pattern was not observed for control participants, who instead were slowest with slow adverbs. This suggests that fast speed information is difficult for PD patients to comprehend when it is used in non-typical situations (i.e. to describe abstract actions). No differences were observed for concrete action sentences.

8.2.3 Semantic Similarity Judgments (SSJs)

Performance in the semantic similarity judgments was quite low (average accuracy of 78% in controls and 70% in PD patients), therefore I decided to remove individual items (one triplet of verbs) if overall accuracy for that item was 50% or less in the control group, in order to minimize the amount of data discarded. Based on these criteria two 'positive vs. negative' trials (targets *to boast* and *to deserve*), two 'movement vs. static' trials (targets *to caress* and *to sprawl*) and three 'thinking v. seeing' trials (targets *to detect*, *to judge*, and *to regard*) were removed. Individual trials were removed if responses were faster than 250ms or outside of 1.5*SD* of a participant's mean response time (13%). One patient was removed for having overall accuracy less than 50%.

Three separate sets of analyses were conducted in accordance with my predictions:

1. Abstract trials: positive, negative, thinking and seeing verbs
2. Full body trials: fast and slow full-body verbs and their matched static verbs (one set of static verbs used in the triplets with fast verbs and one set used in the triplets with slow verbs)
3. Hand/arm trials: fast and slow hand/arm verbs and their matched static verbs (one set of static verbs used in triplets with fast verbs and one set used in the triplets with slow verbs)

Each set was analysed with a 4 (target type) by 2 (group) ANOVA on accuracy and response time.

Based on the predictions and patterns emerging in the data, and to have more power to detect differences, I also ran independent t-tests comparing net accuracy and net response time between PD patients and controls for emotion versus thinking/seeing targets, fast hand versus slow hand targets, and fast full body versus slow full body targets.

8.2.3.1 Abstract trials

Here I contrast accuracy and response time to abstract targets (negative, positive, thinking and seeing verbs). There is no speed information in these words and as such I would not expect any differences between PD and controls to differ according to target types (i.e. I do not expect any interaction).

8.2.3.1.1 Accuracy

Average accuracy is displayed in Figure 8-17.Accuracy was significantly lower in PD patients than in controls (F (1, 17) = 5.41, p =. 03, η^2_p = .24) but there was no overall difference in accuracy across target word type (F (3, 51) = 1.09, p = .36, η^2_p = .06). There was a numerical trend for an interaction between target type and group (F (3, 51) = 2.17, p = .1, η^2_p = .11), with responses to positive and negative targets being less accurate than responses to thinking and seeing targets. When collapsing over emotion trials and thinking and seeing trials, the interaction between target and group became marginally significant (F (1, 17) = 3.45, p = .08, η^2_p = .17). For net accuracy between thinking/seeing and emotion trials, there was a marginal difference between PD patients and controls (t (17) = 1.86, p = .08, d = .85).

Contrary to predictions, accuracy scores suggest that PD patients have difficulty with emotion language compared to abstract language describing thinking and seeing, but control participants do not.

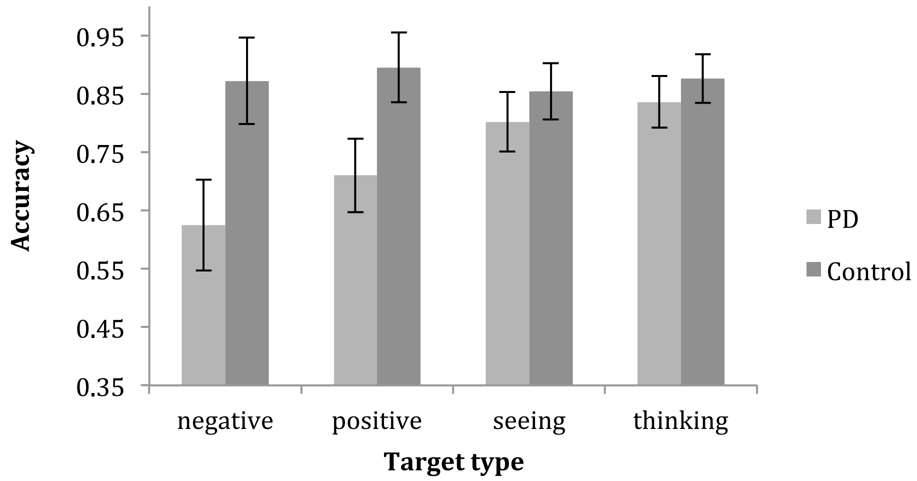

Figure 8-17. Average accuracy for abstract targets in semantic similarity judgments. Error bars reflect 1 standard error.

8.2.3.1.2 Response time

Average response time is displayed in Figure 8-18. PD patients were marginally slower than control participants (F (1, 17) = 4, p = .06, η^2_p = .19) but there was no difference between target type in response time (F (3, 51) = 1.16, p = .33, η^2_p = .06) and no interaction ($F < 1$). There were no differences in net response time ($t < 1$).

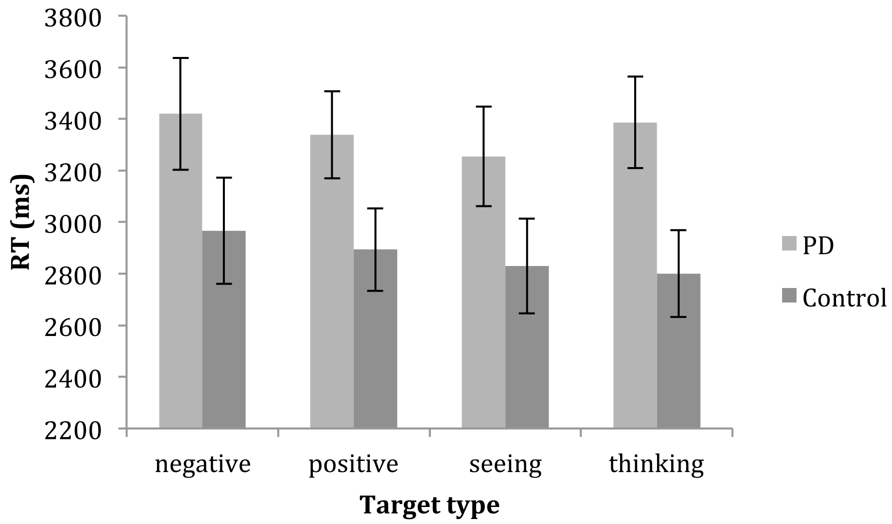

Figure 8-18. Average response time for abstract targets in semantic similarity judgments. Error bars reflect 1 standard error.

8.2.3.2 Full body trials

Here I contrast accuracy and response time to fast full-body targets, slow full-body targets, static targets with fast full-body distractors and static targets with slow full-body distractors. I predict that PD patients will perform worse with fast targets than slow targets (lower accuracy or slower response time) but control participants will not.

8.2.3.2.1 Accuracy

Average accuracy is displayed in Figure 8-19. There was no significant difference across target type (F (3, 51) = 3.15, p = .33, η^2_p = .16) in accuracy. There was no effect of group (F (1, 17) = 1.42, p =. 25, η^2_p = .08), nor was there an interaction between target type and group (F (3, 51) = 1.28, p = .29, η^2_p = .07). For net accuracy between fast full body and slow full body targets, there was no difference between PD patients and controls (t (17) = 1.25, p = .23, d = .58).

Thus there was no evidence in accuracy that PD patients were impaired for slow full-body verbs compared to fast.

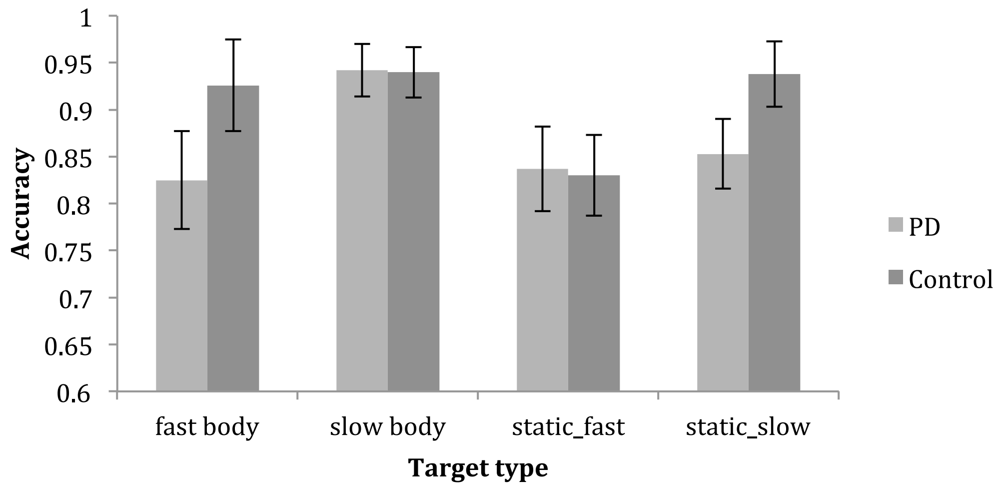

Figure 8-19. Average accuracy for full-body and static targets in semantic similarity judgments. Error bars reflect 1 standard error.

8.2.3.2.2 Response time

Average response time is displayed in Figure 8-20. PD patients were marginally slower than control patients (F (1, 17) = 3.61, p =. 08, η^2_p = .18) but there was no difference across target types in response time (F (3, 51) = 1.46, p = .24, η^2_p = .08) and no interaction (F (3, 52) = 1.08, p = .37, η^2_p = .06). There were also no differences in net response time (t (17) = 1.57, p = .14, d = .7).

Again there is no evidence that PD patients are more impaired in fast full-body verbs than slow full-body verbs.

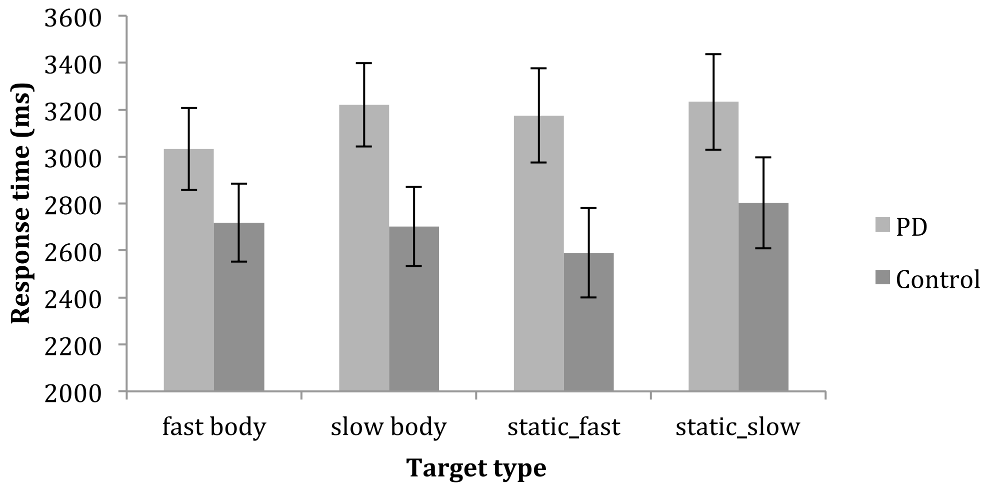

Figure 8-20. Average response time for full-body and static targets in semantic similarity judgments. Error bars reflect 1 standard error.

8.2.3.3 Hand/Arm trials

Here I contrast accuracy and response time to fast hand/arm targets, slow hand/arm targets, static targets with fast hand/arm distractors and static targets with slow hand/arm targets. Here I predict that PD patients will perform worse with fast targets than slow targets (lower accuracy or slower response time) but control participants will not.

8.2.3.3.1 Accuracy

Average accuracy is displayed in Figure 8-21.There was a significant difference in accuracy across target type (F (3, 51) = 5.75, p < .01, η^2_p = .25): responses to slow hand/arm targets were less accurate than all other target types (all ps<. 05). Accuracy did not differ between groups (F = 1, p = .33, η^2_p = .06) and there was no interaction (F < 1).

For net accuracy between fast hand and slow hand targets, there was a marginal difference between PD patients and controls (t (17) = 1.74, p = .1, d = .8) such that net accuracy was larger for controls than patients. Accuracy was higher for fast hand/arm targets than slow hand/arm targets in both groups but this difference was larger in controls. This result has no clear implication for the present hypotheses.

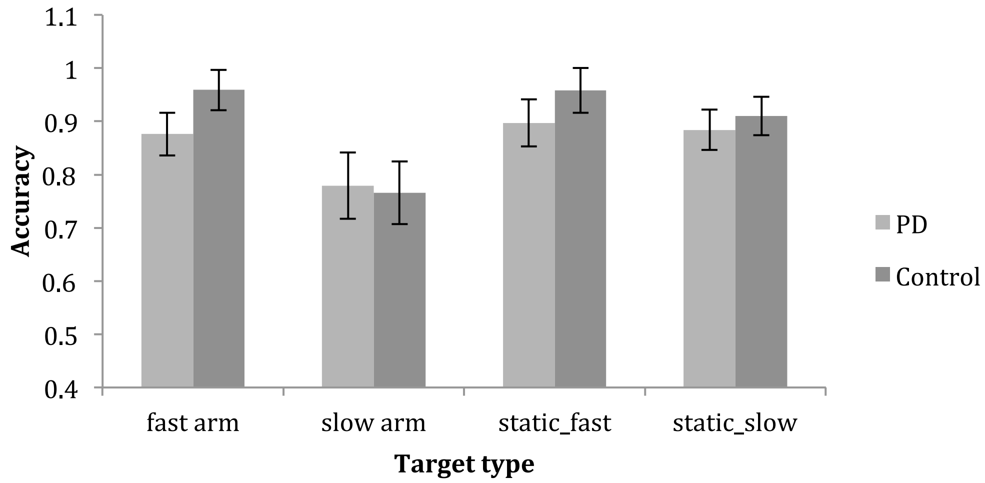

Figure 8-21. Average accuracy for hand/arm and static sentences in semantic similarity judgments. Error bars reflect 1 standard error.

8.2.3.3.2 Response time

Average response time is displayed in Figure 8-22. PD patients were marginally slower to respond than control participants (F (1, 17) = 5.26, p = .04, η^2_p = .24). There was also a significant difference in response time across word types (F (3, 51) = 5, p < .01, η^2_p = .23) with responses slower to slow hand/arm targets than other target types (all ps < .05). However, contrary to the prediction, there was no interaction between word type and group (F < 1). There were no differences in net response time (t (15) = 1.2, p = .25).

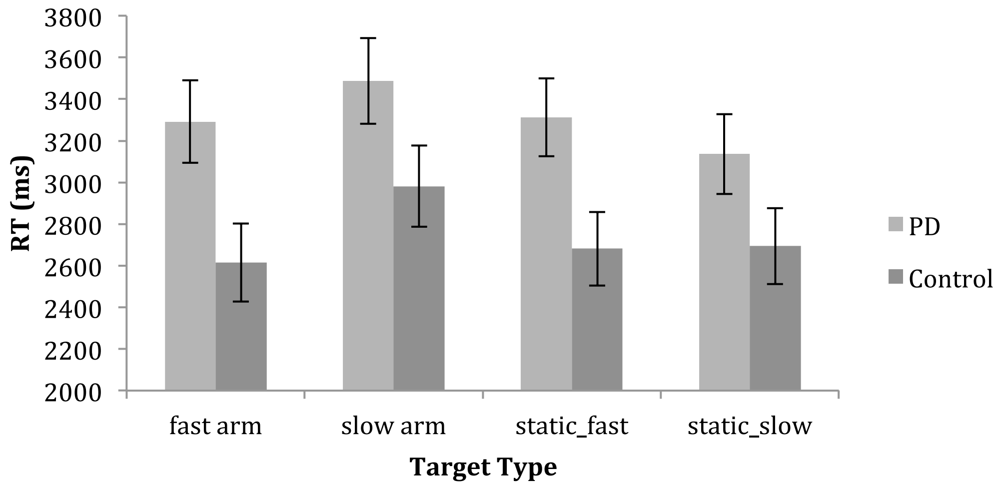

Figure 8-22. Average response time for hand/arm and static sentences in semantic similarity judgments. Error bars reflect 1 standard error

8.2.3.4 Summary SSJs

There were no significant differences in performance on SSJs in line with predictions. Results showed that accuracy was lower in emotion trials compared to thinking and seeing trials, in PD patients but not controls. This, in addition to results from the lexical decision data, suggests that PD may lead to problems comprehending certain types of abstract language.

Table 8 -2. Summary of results for Chapter 8. A tick mark indicates a significant effect. Only effects with p < .05 are included.

Lexical Decision Task

Adverbs	**Accuracy**	**Response Time**	**Priming**
Word Type			
Group		✓	
*Word Type * Group*			
PD vs. Controls	**Net Accuracy**	**Net ResponseTime**	**Net Priming**
Abstract - Fast		✓	
Abstract - Slow			
Abstract - Speed		✓	
Fast - Slow			

Full-body verbs	**Accuracy**	**Response Time**	**Priming**
Word Type	✓	✓	
Group		✓	✓
Word Type * Group			
PD vs. Controls	**Net Accuracy**	**Net Response Time**	**Net Priming**
Abstract - Fast			
Abstract - Slow			
Abstract - Speed			
Fast - Slow			

Hand/Arm verbs	**Accuracy**	**Response Time**	**Priming**
Word Type			
Group			
Word Type * Group	✓		
PD vs. Controls	**Net Accuracy**	**Net Response Time**	**Net Priming**
Abstract - Fast	✓		
Abstract - Slow	✓		
Abstract - Speed	✓		
Fast - Slow			

Sentence Sensibility Judgments

Abstract sentences	**Accuracy**	**Response Time**
Sentence Type		
Group		✓
Sentence Type * Group		✓
PD vs. Controls	**Net Accuracy**	**Net Response Time**
Abstract - Fast		
Abstract - Slow		
Abstract - Speed		
Fast - Slow		✓

Concrete sentences	**Accuracy**	**Response Time**
Sentence Type		
Group		✓
Sentence Type * Group		
PD vs. Controls	**Net Accuracy**	**Net Response Time**
Abstract - Fast		
Abstract - Slow		
Abstract - Speed		
Fast - Slow		

Semantic Similarity Judgments

Abstract trials	Accuracy	Response Time
Target Type		
Group	✓	
Target Type * Group		
PD vs. Controls	**Net Accuracy**	**Net Response Time**
Emotion - Think/See		

Full body trials	Accuracy	Response Time
Target Type		
Group		
Target Type * Group		
PD vs. Controls	**Net Accuracy**	**Net Response Time**
Fast - Slow		

Hand/arm trials	**Accuracy**	**Response Time**
Target Type	✓	✓
Group		
Target Type * Group		
PD vs. Controls	**Net Accuracy**	**Net Response Time**
Fast - Slow		

8.3 General Discussion

The aim of this chapter was to assess comprehension of speed language in patients with PD compared to healthy controls. PD patients have a number of problems with movement, including rigidity and bradykinesia, meaning that they move more slowly than healthy adults of the same age and have difficulty moving quickly. Since they have greater difficulty moving quickly compared to moving slowly, I predicted that they would have difficulty in comprehending language about fast actions compared to slow actions, and more difficulty with both compared to abstract actions. Table 8-2 summarizes the main results of the chapter.

I tested comprehension of speed at several depths of processing, starting with automatic processing and primed lexical decision, moving to more explicit semantic processing and sentence sensibility judgments, finally to semantic similarity judgments, which require explicit, effortful semantic processing. Assessing different depths of processing allows one to ascertain the extent to which speed processing in the motor system contributes to comprehension of language about speed.

Before discussing the present results it should be noted that this dataset is underpowered (testing of patients is still in progress while writing this chapter): here there are eight PD patients and 11 controls included in the analysis and in Fernandino et al. (2013) there were 20 PD patients and 22 controls. Further, since speed is a fine-grained level of action, more statistical power may be necessary to detect differences in fast versus slow comprehension compared to action versus abstract differences (as in Fernandino et al. (2013)). Testing was completed in a fairly small area of South Carolina, which meant that recruitment of patients was difficult. It should therefore be noted that the lack of significant interactions does not yet serve as evidence against a critical role of speed simulation in comprehension of speed in language.

8.3.1 Speed in automatic and implicit processing

Results suggest that there is no crucial role for speed in automatic processing of speed language. For speeded adverbs, full body verbs and hand/arms verbs there was no indication of differences in processing between fast and slow words for PD patients in the lexical decision task.

8.3.1.1 Speed in sentence comprehension

In line with predictions, PD patients did show slower processing of sentences with fast adverbs compared to slow and abstract adverbs, and controls did not. However, this effect was found when the verb of the sentence was abstract but not when the verb was concrete. Thus processing of fast abstract actions was impaired but processing of fast concrete actions was not. Note that in both abstract and concrete action sentences, the fast adverbs were identical. Thus, the slower response time reflects the combination of fast speed with the abstract action and not simply speed implicit in the adverb. This is an unexpected finding, as I would have expected PD patients to have problems with fast concrete actions, because they reflect the type of physical problems that they have, but not with abstract actions, which are not impaired. This result instead suggests that PD patients may have difficulty applying fast speed in atypical, flexible ways. This also suggests that when using abstract or metaphorical language, the motor cortex is still recruited in simulations during comprehension (in line with Boulenger et al. (2009)). An alternative explanation could be that fast-abstract sentences are the most valenced of all sentences types, and PD patients have difficulty with highly valenced, or emotional, language (see below). Although fast and slow adverbs were chosen that imply speed, they also imply other characteristics such as the mood or motivation of an agent in action. Examples of fast adverbs that imply other characteristics, such as valence, include *fiercely* and *frantically*. However, the adverbs used had been rated as neutral in terms of valence, so this is unlikely to be an explanation. It should also be noted that the abstract verbs and concrete verbs used in the sentences were matched on valence. It may be possible however that combining the adverbs with the verbs changes the valence so that they are not simply an average of the two words. For example, the act of debating is likely to be more valenced in "*fiercely debated*" than in "*eagerly debated*". Ratings of whole sentence valence will be needed to investigate this suggestion. A related explanation could be arousal. Although adverbs and verbs were matched according to valence, measures of arousal were not checked. Arousal has been described as one of the three components of emotion (including also valence and dominance), and measures range from "calm'' to "excited'' (Osgood, Suci & Tanenbaum, 1957). Thus, if Parkinson's patients have difficulty with emotional language, then language with high levels of arousal may be problematic. It seems likely that the fast adverbs used here would rate higher in arousal than the slow adverbs used (e.g. compare *urgently*, *frantically* and *suddenly* with *casually*, *calmly* and *leisurely*). However, if arousal played a role, then performance should have been slower when fast adverbs were paired with both concrete and abstract verbs, which was not the case. Yet, as mentioned above, combining the adverbs with abstract verbs may in fact increase the emotional content, making those sentences more difficult.

8.3.2 Speed in explicit processing

At explicit levels of processing (semantic similarity judgments), no effects of speed were observed. It is possible that the design of the semantic similarity judgment task is not sufficient to reveal problems in comprehension of speed in PD patients. The task may be too difficult, particularly when matching movement and static trials. The verbs denoting static movements were chosen by experimenters only and not rated according to amount of movement by a set of naïve participants. Some 'static verbs' may imply some movement, although the end point or goal of that movement is to be still. For example *to retire, to cease, to stop* imply movement to some extent (i.e. the stopping of movement). Further, although verbs such as *to sit, to stand* and *to squat* were intended to refer to being in a stationary position, they may have instead evoked movement into those particular positions. Matching to targets on these trials becomes even more difficult when comparing static actions against slow hand actions that imply very little movement e.g. *to feel* and *to stroke*. Comparing the current task with the semantic similarity judgments used in Fernandino et al. (2013) highlights the difficulty. In their task, on each trial two of the words had similar meanings (e.g. *to stroke* and *to caress*, with *to embrace* as the foil). Although the foil is related in meaning it is clear that the matching words have more or less the same meaning. In the present study however, two words match according to one dimension but the full meanings of the words are not the same. For example, *to sneak* and *to wander* match in that they are both slow movements, but sneaking implies a sly or shifty movement and wandering implies moving without any particular aim. The two tasks are therefore not comparable. Thus, although differences in speed processing may be revealed with more power in the study, it is also possible that this task with this particular set of items is not suitable to assess the level of comprehension of speed intended.

8.3.3 Abstract comprehension in Parkinson's disease

Results also present an interesting finding that was not part of the predictions of this thesis. PD patients appear to have more difficulty with comprehension of abstract language compared to controls. PD patients showed reduced priming for abstract adverbs compared to fast and slow adverbs, lower accuracy in lexical decision to abstract verbs compared to hand/arm verbs and lower accuracy for emotion targets compared to thinking and seeing verbs in the semantic similarity judgments. These patterns did not exist for controls. Thus, PD patients were impaired at both automatic and explicit levels of processing abstract language. One explanation could be in terms of valence. Abstract adverbs in the lexical decision task were not controlled for valence, and in fact many turned out to be highly valenced e.g. *terribly, miserably*. Note that the abstract adverbs used in the sentence sensibility task were matched on valence, which may be why no impairments were observed here. That PD patients may have difficulty processing emotion language is in line with the idea that they have problems recognizing emotions due to their inability to fully experience facial expression (e.g. Mermillod et al., 2011). However, patients did have lower accuracy on abstract trials compared with hand/arms verbs, which had been rated as neutral valence in the norming procedure. This suggests that there may be something inherent in abstract language in general, rather than valence, which PD patients have problems with. However, the abstract verbs were rated on valence by only seven subjects, so strong conclusions cannot be drawn about their neutrality.

Another possible explanation for poorer performance with abstract language is that PD patients have problems with executive function. Impairments in executive function including maintenance of objects in working memory and allocation of attention have been reported in PD (Dubois & Pillon, 1997). Abstract words may be more demanding on executive control because they are associated with a greater number of senses and more varied linguistic context (Fernandino et al 2013). It has been suggested that the meaning of abstract words is based on a wider range of simulations than that of concrete words and the type of information and situations relevant for abstract meaning is more difficult to access (e.g. Schwanenflugel & Shoben, 1983). Thus more cognitive control is required to filter out irrelevant information during comprehension (Fernandino et al. 2013). That PD patients might have problems with this resonates with research suggesting PD leads to the inability to suppress previously learned responses (Cronin-Golomb, Corking & Growdon, 1994). The comprehension of abstract language in PD is clearly a topic that requires further investigation.

Fernandino et al. (2013) also suggest that the executive deficits occurring in PD patients may make it more difficult to find predicted semantic deficits in patients. A decline in executive processing may affect controlled measures of task performance such as response time, which would reduce differences between conditions. Thus, the more impaired a patient may be, the more difficult it may be to detect problems in specific semantic categories. Executive function in PD is thought to decline rapidly around 13 years after diagnosis (Aarsland, Muniz & Matthews, 2011). The average length of time since diagnosis for the patients in the present study was 7.9 years, and 4 patients were close to or greater than the 13 year mark. Thus, perhaps the progression of executive dysfunction in this selection of patients is too severe for semantic difficulties to be detected. Additionally, although patients were removed from the analysis for having MoCA scores of less than 22, as this would suggest PD dementia, a score between 22 and 26 does suggest mild cognitive impairment (MCI). Only two patients in the PD group scored greater than 26, suggesting that the majority have cognitive impairments, which may have led to greater difficulty with abstract language.

8.3.4 Further investigation

It would be interesting to conduct further analyses with the data, investigating how UPDRS scores (assessment of motor difficulties) and time since diagnosis are correlated with differences in comprehension between PD patients and controls. I would predict that this difference would be larger the higher the UPDRS score and the longer length of time since diagnosis (although progression of the disease is variable). That is, the more impairment in motor capabilities a patient has, the more they should be impaired in language about fast and slow actions. Unfortunately, due to the small number of patients and small amount of variability in their UPDRS scores, I cannot conduct these analyses with the present data set.

8.4 Chapter conclusion

With a small number of patients and controls I have found evidence for slower processing of sentences with fast adverbs, when the adverb modifies an abstract action, in PD patients compared to controls. Thus, PD patients, who have difficulty moving quickly in their daily lives, also have difficulty processing fast speed at implicit levels of comprehension. Moreover, this deficit in comprehension of fast speed is only observed for abstract actions, but not concrete actions. This may suggest that PD patients have difficulty with fast speed in language when they are required to use the speed information flexibly, or to apply it in unusual scenarios using processes that may tax executive processing. At explicit levels of comprehension, when comparisons between stimuli are required, no significant effects were found. This level of comprehension requires the participant to think explicitly about the meaning of the verbs and make decisions, thus I would expect it would be the level in which sensorimotor systems would contribute the most because the full meaning of a word would need to be accessed. Comprehension of speed does not appear to be affected in automatic processing in PD. In comparison to other studies that have found problems with action language at this level of processing in PD patient (Fernandino et al. 2013), speed may be too fine-grained to be a necessary component of comprehension at this level.

Results also suggest that PD patients have difficulty in processing abstract language, both at conscious and preconscious levels of processing. Possible explanations for this could be that PD patients have difficulty with emotion due their inability to produce facial expressions, or that abstract language requires greater cognitive effort and executive functioning. This finding requires further exploration with tasks and stimuli designed to specifically test a variety of abstract language.

Chapter 9 General discussion and conclusion

How do we map words and sentences to their corresponding concepts in order to comprehend and communicate effectively? Embodied theories propose that understanding meaning in language requires mental simulation taking place in the same modality-specific systems involved in perceiving and acting in the world, such as perception and action systems (e.g., Barsalou, 1999a; Stanfield & Zwaan, 2001; Glenberg & Kaschak, 2002). This mental simulation grounds language in the real world and moves away from abstract, symbolic representations of word meaning. The aim of this thesis was to investigate how language about speed of motion and action is understood from an embodied language perspective. According to this approach, understanding words and sentences that describe speed will involve simulating speed in the brain's sensorimotor systems, the same systems involved in perceiving speed in the world.

The literature now contains support for embodiment with demonstrations of simulation of a number of features of action and perception. Investigating comprehension of speed language adds and extends the dimensions within this literature. Speed is computed using both spatial and temporal information, so it is a more complex semantic feature in comparison to those investigated so far such as object shape and orientation (e.g. Stanfield & Zwaan, 2001, Zwaan et al., 2002, Zwaan et al., 2004). Further, speed if a more fine-grained dimension of motion events. This is especially important because embodied theories are underspecified in terms of how much information from an event is contained in mental simulations (Sanford, 2008), what features are included or at what grain information is represented.

In this chapter I will start by providing a summary of the experimental questions outlined in Chapter 3 and the evidence reported throughout the thesis. I will then discuss in more detail the main findings and how my research contributes to the main issues of embodiment that I outlined in Chapter 2 and 3 before suggesting some future directions for work in embodiment. I will then conclude by sketching the contributions of vision, action and audition to the mental simulation of speed.

Within my experiments I used both words and sentences that describe speed thereby assessing to what extent the presence and nature of speed simulations differ between different linguistic contexts. In addition, I used a range of experimental paradigms: behavioural testing with response time and accuracy measures, visual psychophysics, eye-tracking and patient work in order to thoroughly investigate the nature of speed simulation. Testing comprehension of speed across a variety of conditions means I had the opportunity to assess the boundaries of embodied effects for speed and reveal any factors important in moderating the presence and nature of speed simulations.

9.1 Research questions

Below I reiterate the main research questions as outlined in Chapter 3 and summarize the results of my research.

9.1.1 The influence of perceptual processing on speed word comprehension (Chapter 4)

If comprehension of speed words involves processes used in real-world speed perception, then combining speed in language with perceptual speed stimuli should affect processing to some extent. The first experimental chapter investigated whether combining speed words with perceptual speed affects processing of those words. Perceptual speed of different modalities (auditory and visual) was combined with a lexical decision task on single verbs that describe fast and slow motion (e.g. *dash*, *amble*). To create visual speed, fast and slow moving horizontal lines (Experiment 4-2) and fast and slow moving vertical lines in perspective (Experiment 4-4 and 4-6) were used. To create auditory speed, fast and slow moving beeps (Experiment 4-3), fast and slow moving white noise (Experiment 4-5 and 4-7) and fast and slow footsteps sounds (Experiment 4-8 and 4-9) were used. Each perceptual stimulus was presented for three seconds before a word was presented (visually or auditorily) to which participants had to decide if it was a real word or not. I predicted that if speed simulation does occur for single speed verbs then responses should be different when the speed of a verb matches the speed of perceptual stimulus (congruent) compared to when they do not match (incongruent).

Results showed that speed simulation does occur for single word comprehension when there is no sentence context. However, there were three constraints on whether or not speed simulation was observed in these experiments. First, reaction times showed interactions between verb speed and perceptual speed, but only when the perceptual stimulus was vertical lines moving in perspective or the sound of footsteps, but not the other types of auditory and visual stimuli. Lines moving outwards in perspective, creating a sense of moving forwards in the perceiver, and the sound of footsteps emphasize motion with the body whereas the other perceptual stimuli portrayed a more abstract motion depiction. That simulations only occur when perceptual stimuli imply bodily motion suggests that speed simulations reflect the full meaning of the verbs in terms of an agent moving quickly or slowly instead of a schematic depiction of speed that is abstracted away from agents. A further condition that determined whether or not speed simulation was observed was whether the modality in which the perceptual and word stimuli were presented in matched (i.e. visual lines and visual words, auditory footsteps and auditory words). It is thought that because the perceptual stimuli and words were presented consecutively then they were less likely to overlap in processing than if they would have been presented simultaneously and even less likely if they were of different modalities. Finally, the nature of the interaction between word speed and perceptual speed differed between auditory and visual modalities. When both the perceptual and word stimuli were visual, facilitation in responses was observed (faster response time for congruent trials). Conversely, when both the perceptual and word stimuli were auditory, interference to responses was observed (slower response time for congruent trials). These differences are thought to be due to differences in the overlap of features between the perceptual and verbal stimuli and not modality differences, as discussed in more detail below in section 2.4.

9.1.2 The influence of speed words on perceptual processing (Chapter 5)

This chapter looked at the converse effect of the bidirectional relationship between speed in language and speed in perception by testing whether comprehending speed words affected the visual perception of speed. Participants passively listened to verbs that described fast and slow actions while performing a visual speed discrimination task. They were first presented with a ‘standard’ sinusoidal grating moving at a fixed speed (3, 5 or 8Hz) and then were subsequently presented with comparison gratings to which they had to decide whether they were moving faster or slower than the standard stimulus. By fitting a psychometric function to the data, measures of both perceptual sensitivity (speed discrimination threshold) and perceptual bias (point of subjective equality) could be extracted. Listening to fast and slow speed verbs was found to affect measures of point of subjective equality only and not speed discrimination threshold. Point of subjective equality describes the perceived speed of the standard grating and reflects perceptual bias. This suggests that the interaction between speed in language and speed in visual perceptual reflects perceptual biases and does not affect perceptual sensitivity. Further, this effect was observed only when the standard speed was 3Hz and not at 5Hz or 8Hz. At 3Hz the speed discrimination task was more difficult: speed discrimination is poor at the extremes (i.e. at very slow speeds) (De Bruyn & Orban, 1988) and perception of slow speed has been shown to be particularly difficult in the periphery (in comparison to central presentation) (Maunsel & van Essen, 1983). Results therefore suggest that semantic speed information is more likely to interact with perception of visual speed when the sensory signal is reduced and therefore the task is more difficult.

9.1.3 The influence of speeded actions and perceptual speed on speed sentence comprehension (Chapter 6)

In this chapter I moved to comprehension of speed in sentences and tested whether sensorimotor speed can affect comprehension by manipulating auditory speed and speed of action. In the first experiment participants listened to the sound of fast and slow footsteps before and during visual presentation of sentences and had to make sensibility judgments on the sentences. In the second experiment, the speed of participants' movement in a movement task was manipulated by wearing arm and leg bands that did or did not contain weights, after which they completed the same sentence sensibility judgment task. Sentences described both fast and slow full-body actions (e.g. running) as well as fast and slow actions performed with the hands (e.g. grasping). Additionally I included both speed verbs and speed adverbs to see if the way in which speed is encoded affects the nature of speed simulation.

Not surprisingly, given the results of the experiments with single words, results suggest that comprehenders do simulate speed of actions as described in sentences and that these simulations include auditory speed information and action speed information. Auditory speed simulation for concrete action types using both adverbs and verbs was suggested by marginal interactions. However differences were observed between the different types of action. When combining sentences with the sound of fast and slow footsteps a marginal interaction was found such that responses were more accurate when speed of action described in the sentence matched the speed of auditory footsteps for sentences describing speeded hand/arms actions and sentences with speeded adverbs paired with concrete actions. However, the opposite interaction was found for sentences describing full body actions: responses were less accurate when the speeds matched. This suggests that speed simulations include specific features about the effector used in the action (e.g. hands, arms). When the sentences described action with the whole body there was a large overlap in activation from the auditory stimulus and the speed simulation, which led to interference: the simulation matched the sound of footsteps in terms of actions features (leg movements) and speed. When the sentence described actions with the hands/arms there was only partial overlap in activation, which facilitated responses: the simulation matched the auditory footsteps in terms of only speed and not action features.

When manipulating participants' movement speed, no evidence was found for action simulation with sentences in which speed was encoded in adverbs. For hand/arm sentences there was no evidence of the simulation of speed specifically, but there was for action more generally: responses to hand/arm sentences were more accurate in the condition with weights compared to the condition without weights, but there was no such difference for abstract sentences. One explanation for this effect is that wearing weights taxes the motor system to a greater extent than when not wearing weights, leading to greater motor activation, which then facilitated processing of the hand sentences in general. For full body sentences, an interference effect was observed with responses less accurate in congruent conditions (i.e. fast sentences with no weights and slow sentences with weights) than incongruent conditions. Again, this is interpreted in terms of feature overlap: the motor task matches the actions described in the sentence in terms of speed as well as effectors used in the action (the whole body).

9.1.4 Eye movements and the mental simulation of speed in sentences (Chapter 7)

This chapter investigated speed simulation in sentences in a more naturalistic manner by measuring eye movements during comprehension. Spoken sentences were presented to participants whilst they viewed a visual scene that contained agents and destinations that were depicted in the sentences. Sentences described an agent moving to a destination at a fast or slow speed, with speed encoded either in the verb or adverb of the sentence. Additionally, the speaking rate of the sentence was manipulated to be fast or slow. Eye-movements towards objects in the visual scenes were measured during comprehension.

Time spent looking at objects in the visual scene was affected by the interaction between speed of the verb/adverb of the sentence, speaking rate of the sentence and configuration of the corresponding visual scene. Simulations of speed were observed when sentences were spoken slowly but not when they were spoken quickly. This suggests that speed simulation may not occur in contexts in which there is time pressure and instead a shallow interpretation of the sentence will suffice. For sentences with speed verbs, participants spent longer looking towards the target destination for sentences describing slow motion compared to fast motion, but only when the scene was unambiguous (i.e. contained only the agent and target destination described in the sentence and not a distractor destination). When the scene was ambiguous, containing a target distractor, longer looks for sentences describing slow compared to fast motion were found on looks to the agent, or sometimes the ambiguity led to no differences at all. This suggests that speed simulation is flexible and the nature of the simulation develops in line with the information currently available in the environment. When speed was described by the adverb of the sentence, the opposite effect was found, with longer looks towards the target destination for sentences describing fast motion compared to sentences describing slow motion (when there was no distractor). One potential explanation for the difference between verbs and adverbs is the timing of speed information in the sentence. For adverbs, the speed information comes early, before the action described by the verb, but for verbs, speed is tied to the action event. This means that for adverbs, speed can more easily modify the event and is not constrained by a simulation of motion that is already developing (as is the case with verbs). For adverb sentences, looks are directed towards the target when the simulation is complete (meaning that looks are directed earlier and hence longer for fast events). For verbs sentences, looks are directed towards the target during the simulation, because the target is as integral part of the verb simulation. Looks are directed *away* from the target when the simulation is complete, leading to longer looks for slow motion events compared to fast motion events. Another potential explanation is in terms of linguistic focus (Taylor & Zwaan, 2008). Using a speed adverb may focus attention on the manner of motion but using a verb instead focuses attention on the completion of the event.

Thus evidence for the online simulation of speed during spoken sentence comprehension was demonstrated using an experimental paradigm that provides a naturalistic observation of simulation (i.e. does not require explicit judgments about sentences). Eye-movements are sensitive to subtle semantic differences such as the fine-grained dimension of speed.

9.1.5 Is speed processing in language affected by deficits in the motor system? (Chapter 8)

The final experimental chapter served as a crucial test of an embodied theory of speed by investigating whether individuals with impairments in movement, particularly in moving quickly, also have difficulty understanding speed in language. I used a range of language related to speed, including speed verbs and adverbs, as well as abstract verbs and adverbs, and addressed comprehension of speed language in patients with Parkinson's disease (PD) and healthy controls at various depths of processing: lexical decision with priming assessing comprehension at subliminal levels, sentence sensibility judgments assessing implicit comprehension and semantic similarity judgments assessing explicit semantic processes.

Results showed that PD patients are slower to comprehend sentences with fast adverbs compared to slow and abstract adverbs when they are used in sentences describing abstract but not concrete actions. This pattern is not observed in control participants. This suggests that comprehension of fast speed is impaired in PD patients when they have to use speed information in an unusual or flexible manner, perhaps because they have to access speed information at a deeper and more explicit level in order to apply it to non-concrete events. Although there is no evidence that PD patients had greater difficulty than controls with the explicit semantic similarity judgments. There was no evidence that comprehension of speed is affected in PD at more automatic levels of comprehension. Previous studies have shown deficits in processing of action language at this level in PD. Thus, speed information may be too fine-grained to be included in simulations that are fast and automatic and instead may only affect simulations at deeper processing levels (i.e. sentence comprehension).

PD patients were also found to be impaired in abstract language on a number of measures but control participants were not. Possible explanations for this impairment are that abstract language strongly relies on emotional information (Vigliocco et al, 2013), which is problematic for PD patients due to their inability to produce facial expressions (Mermillod et al., 2011). Alternatively, since abstract language is more complex with a greater number of senses and possible meanings (Fernandino et al., 2013), PD patients may struggle to comprehend due to their deficits in executive processing (Dubois & Pillon, 1996).

9.2 Results in relation to current issues in embodiment

Below I discuss the above research findings in relation to current issues in embodied research: features, specificity, mental imagery versus simulation, context and the continuum of embodiment, linking them with work in the literature.

9.2.1 Features

As described in the beginning of this chapter, it is at present unclear to what extent mental simulations during language comprehension reflect the full details of real world experience. By investigating the simulation of speed I have explored a fairly neglected feature in terms of embodiment, a feature that is more fine-grained than most in the literature. It has been suggested that perceptual simulations are schematic (Zwaan, 2003; Barsalou, 1999a) and thus it is conceivable that they only include salient or coarse details. That evidence exists for speed simulation shows that simulations go beyond a schematic reconstruction of action events in general, to a further level of detail, including fine-grained information about the manner of action.

Much work in the embodied literature tends to provide evidence for the simulation of a particular type of language or feature in a single modality, for example Stanfield & Zwaan (2001) investigated the simulation of orientation using visual stimuli only. For the first time I have provided evidence for simulation of both auditory and visual information using the same stimuli and the same task (Chapter 4). Thus, like real-world experience, speed simulations reflect experience in multiple modalities. Although work in the present thesis shows to some extent different results for auditory and visual simulations, it is thought that these differences reflect idiosyncrasies of the experimental paradigm (see below) rather that the composition of the simulations themselves. That is, there is no evidence that visual or auditory information is more important to speed simulations. It remains to be investigated whether speed simulations would be observed in other modalities, such as the tactile domain, domains that may not provide such precise information as vision and audition.

My research suggests that simulations of speed include visual, auditory and action information and are specific to the body in motion, including details about the types of effector used in the action. Simulations are not fixed but are dynamic and changeable depending on contextual factors (see discussion of context below). They can be affected by information in the environment and integrate this information into the simulation. Evidence from this thesis (Chapter 5) suggests that speed simulations may not occur within low-level perceptual areas but at higher levels of processing, at more semantic levels. Interactions between speed in semantic information and speed in sensory information may be found in regions where modality-specific information is integrated (e.g. lMTG) within typically defined 'language regions' rather than perceptual regions (Francken et al., 2014), or in convergence zones, near to but not in primary sensory regions (e.g. Barsalou, 1999a). This finding is in line with results showing that speed simulations include information about the body and effectors (Chapters 4 and 6): at early visual areas information such as biological motion and agency would not be processed (Gennari, 2012).

9.2.2 Specificity

Looking at speed in language also addresses the question of specificity of simulations: speed information is not crucial to understand an event such as an agent moving to a destination, but for a simulation to accurately reflect real-world experience it should include this level of detail. Thus, results of this thesis support the idea that simulations can include fine-grained reflections of real-world experience reflecting specific details about manner of motion.

Further details of the specificity of speed simulations in terms of effectors used are revealed in Chapters 4 and 6. Chapter 4 demonstrates that speed simulations for single verbs specifically reflect speed of motion with *the body*. Simulations of speed do not appear to be an abstracted depiction of speed, but instead are tied to speed of an agent. This specificity was revealed in the finding that abstract visual and auditory depictions of speed such as a line moving horizontally quickly or slowly or the sound of fast and slow beeps or white noise did not affect responses to speed verbs, but depictions of speed that involve the body did (the sound of fast and slow footsteps or fast and slow lines moving in perspective creating a sense of forwards motion). However, in other studies that use a similar paradigm but investigate direction simulation (Kaschak et al., 2005; Meteyard et al., 2009), abstract stimuli did interact with word and sentence meaning. For example, Kaschak et al. (2005) used moving black and white lines that did not imply any type of agent or object to depict different directions of motion. One explanation for why abstract depictions of speed did not work here may be that speed is subtler, more abstract, and needs more context than other dimensions like direction. For example, it is easy to think about the concept of "up" without having to think about an agent or object, but thinking about "fast" requires thinking about something or someone in motion. Thus speed cannot be abstracted away from agents but must be integrated with them. Direction instead is more salient and necessary in understanding motion events and therefore simulated more independently. An alternative reason could be the types of words used in the experiments. For example, the verbs used in

Meteyard et al., (2009) did not describe actions specifically performed with the body but actions that could also be applied to non-biological entities. For example, the words *rise* and *fall* could describe movement of a number of inanimate objects such as a balloon or a rock as well as the movement of humans or animals. The items used in the present experiments however strongly refer to actions performed with a human body and cannot be applied to inanimate objects. Since the items in Meteyard et al., (2009) do not specifically refer to actions of humans or animals they possibly involve motion simulations that are more abstract and schematic. Thus, there may be large differences in the nature of simulations for language about direction and language about speed, with direction allowing for more abstract simulation but speed requiring particular agents.

That simulations for speed verbs were only found when combining them with body-relevant stimuli raises the question of whether speed simulations are egocentric. The idea of mental simulations having an egocentric perspective has been suggested by other work. The body-specificity hypothesis (Casasanto, 2009) proposes that we tend to comprehend action language in terms of our own actions rather than that of others because our bodies constrain the way that experience shapes our concepts. Evidence suggesting the self-relevance of simulations includes that of Rueschemeyer et al., (2010), who found that motion sensitive area MT is activated by sentences describing motion towards a participant but not sentences describing motion away from the participant. It seems unlikely though that speed simulations could only reflect actions with one's own body since we have a wealth of experience perceiving others moving quickly and slowly in the world. It might be possible that the default for speed simulations without any sentence or narrative (or situational) context is egocentricity, but when given the correct context simulation of others in action is possible. Evidence from Chapter 7 shows that speed of others can be reflected in simulations, as eye-movements towards agents and objects in a scene were sensitive to speed in a manner consistent with the motion of those depicted objects (i.e. motion of an *other*, not the self). If it is the case that default speed simulations for single words are egocentric but they are not when given the correct sentence context then perhaps a more abstract prime, such the horizontal moving prime in Chapter 4, would affect comprehension of sentences describing an agent moving quickly or slowly, because the two types of motion would match (i.e. we often perceive agents moving across a horizontal plane). This idea is in lie with results of Chapter 7 and discussions elsewhere (Zwaan, 2014; Lebois et al., 2014) that describe how mental simulations are dynamic and differ depending and task and other contextual factors.

As well as simulations of speed specifically reflecting motion of the body, speed simulations also code for the specific effector used in the action: whether it is an action performed with the whole body such as *running* or instead the hand/arm such as *grasping*. This 'effector specificity' (Hauk et al., 2004) was evident in the finding that the sound of fast and slow footsteps interfered with comprehension of sentences describing fast and slow full body actions (e.g. sentences about *running*) but facilitated comprehension of sentences describing fast and slow hand actions (e.g. sentences about *grasping*, Chapter 6). Interference was thought to occur because the sounds of footsteps and the simulation used in the full-body sentences overlapped in terms of both speed and the specific effectors used in the action (i.e. there was full overlap between processing). Hand sentences however did not overlap with the sound of footsteps in terms of effector (the sentences encoded the hands/arms and the sounds encoded the feet) but did overlap in speed (when the speeds matched). Thus the sounds and the sentences here only partially overlapped, and this acted as a head start in processing of the sentence. This effect was also supported in the interaction between action speed and sentence speed: when participants were forced to moved slowly by wearing weights and complete a movement task, accuracy in comprehension for sentences describing full body actions was lower than when they completed the task without weights (i.e. accuracy was lower when speed of the whole body matched speed in sentences about the whole body).

9.2.3 Mental simulations are post-comprehension mental images, and other criticisms

My research adds to the discussion of whether embodied results reflect mental imagery or mental simulation (e.g. Mahon & Caramazza, 2008) by using eye tracking combined with a task that does not require explicit judgments about the linguistic stimuli (Chapter 7). By having participants simply listen to sentences, sometimes responding to simple comprehension questions, the likelihood of them engaging in explicit imagery is reduced. This is not the case for other studies such as Zwaan et al (e.g. Stanfield & Zwaan, 2001, Zwaan et al., 2002, Zwaan et al., 2004) where participants are asked to decide if a picture was mentioned in a sentence or not, thereby encouraging them to visualise the described objects. Further, mapping the time course of speed simulations in my eye-tracking data suggests that they are built online during comprehension, rather than being a post-comprehension process. Although not directly tested, an effect of speed words in the speed discrimination task (Chapter 5) also supports an argument for the mental simulation of speed rather than mental imagery. In this task, speed words were comprehended passively (and repeated over and over) and were of no relevance to the task. Moreover, the speed discrimination task was both inherently difficult and very fast, meaning that participants would have little cognitive resources or time to engage in any imagery or explicit thoughts about the verbal stimuli.

Another argument from critics of embodiment is that mental simulations are not crucial to comprehension but only epiphenomenal (Mahon & Caramazza, 2008). By testing comprehension of speed in Parkinson's disease (PD), I assessed whether or not speed in action simulation is critical to comprehension of speed language. PD patients have reduced activation in the motor cortex and therefore have difficulty moving. If speed representations in the motor cortex are crucial to speed simulations in language then PD patients should be impaired with speed language compared to other non-action language. Although the data presented in Chapter 8 is currently underpowered, at present it suggests that PD patients are not impaired with speed language when it is processed implicitly (priming scores) or when understood explicitly (semantic similarity judgments) but they are when fast speed information is used in an atypical way (sentence sensibility judgments on speeded abstract actions). This suggests that speed simulation is crucial in comprehension of speed language but perhaps only when comprehension is difficult or speed information needs to be manipulated. At more implicit levels of processing, PD patients may rely on other information, such as simulations in non-impaired modalities or linguistic associations (Barsalou et al., 2008).

Thus, the data presented in this thesis supports the view that speed simulations are automatic in that they do not require conscious strategies (although they do not necessarily occur in all contexts) and that these simulations are critical to deep levels of the comprehension of speed.

9.2.4 Context

Recently, embodied research has begun to discuss the claim that simulations are dynamic and context dependent (Zwaan 2014; Lebois et al., 2014), being relied upon more or less in different linguistic and situational contexts. Results from this thesis support this view. Within the experiments here I manipulate a variety of contexts, including linguistic type, modality of perceptual and verbal stimuli, supporting visual scenes and speaking rate of presented sentences. Below I discuss how these manipulations affect the nature of any simulation effects.

9.2.4.1 The role of modality

In Chapter 4, interactions between speed of verb and speed of perceptual stimuli were only observed when the modality of the speed stimulus and the modality of word presentation matched. This might suggest that simulations develop in a manner consistent with the way in which language is presented. For example, when a word or sentence is presented visually, visual simulations of the referent may be produced, or simulations that are dominated by visual information. Connell & Lynott (2014) found that for words presented visually in a lexical decision task and reading-aloud task, words with strong visual associations were processed faster than words with strong auditory associations, because visual attention was engaged (and the converse for naming words with strong auditory associations). This shows that the type of attention directed to the verbal stimuli (i.e. visual or auditory) can affect the way that semantic information is retrieved. But, although perceptual attention may facilitate processing of a word whose meaning is strongly dominated by the same modality, it seems unlikely that it would block simulations in other modalities (i.e. this would not explain the lack of effects in the cross modal experiments of Chapter 4). Moreover, simulation effects are observed in Chapter 6 and elsewhere (Kaschak et al., 2005; Brunye et al 2010) when the verbal and perceptual stimuli are of different modalities. A more plausible explanation for why simulation effects were only observed with matching modalities involves details of the experimental method, particularly the importance of timing in stimulus presentation. In Experiment 2 of Chapter 6 simulation effects were observed when sentences were presented visually and the speed stimuli were presented auditorily and in Chapter 5 an effect of speed was observed when verbs were presented verbally but the speed task was presented visually. Additionally, results in both Kaschak et al. (2005) and Brunye et al. (2010) are found when the modality of verbal and perceptual stimuli is different. The main difference between these tasks and those in Chapter 4 is that the verbal and perceptual stimuli are presented simultaneously, whereas in Chapter 4 the perceptual stimuli precede the verbal stimuli. When stimuli are presented simultaneously they are more likely to interfere (or facilitate) with each other because processing resources are being recruited at the same time (or attentional resources are being recruited, Connell & Lynott, 2012b). When perceptual stimuli precede the verbal stimuli there is a lower chance of an interaction occurring because one process may have been completed before the other begins. When both are of the same modality however an effect is more likely to occur due to residual activation in that modality. For different modalities, the two processes are more likely to be separated, because switching between modalities can result in temporal processing costs (Pecher et al., 2003).

9.2.4.2 Attentional demands

Results suggest that attentional or processing demands may affect whether or not speed simulations are recruited in comprehension. For example, no effects of verb speed were found in the speed discrimination task (Chapter 5) when the task was very long and tiring. Similarly, no evidence of speed simulation in eye movements was observed in Chapter 7 when the speaking rate of the sentences was fast. Thus, when comprehension is at a shallow level either due to lack of attention (Chapter 5) or because of environmental factors such as time constraints or a noisy signal (Chapter 7) speed simulation does not occur. This also resonates with findings in Chapter 8 in which speed information is not simulated at implicit levels (in priming effects). Speed simulation appears to require greater context or greater depths of processing than action simulation in general. Work elsewhere (Barsalou et al., 2008) suggests that simulations take time to develop and that when a quick response is required in a comprehension situation lexical associations (statistical information about the co-occurrence of words) are more likely to be activated than simulations (Louwerse & Jeuniaux, 2008) (see Chapter 1 Section 4.5). Thus, the conditions for which no evidence of simulation was found in Chapters 5 and 7 likely reflect the type of comprehension situations for which lexical information would dominate, or possibly the simulation of more salient features. That is not to say that statistical linguistic information is being used to aid in completion of the task, but rather to emphasize that embodied simulations may not have sufficiently developed because comprehension was shallow.

9.2.4.3 Task difficulty

Related, in terms of when speed simulations can affect perceptual processes, task difficulty seems to be an important factor. Speed words affected performance in the speed discrimination task (Chapter 5) in terms of point of subjective equality only when conditions of the task were very hard (when the standard speed was very slow). This suggests that when perception is particularly difficult it is more susceptible to influence from other processes, such as semantics. This idea is supported in other studies investigating the effect of language on perception. In a direction discrimination task, Pavan et al (2013) found that listening to direction verbs affected perceptual sensitivity when the visual stimuli were presented at threshold but not when presented suprathreshold. A similar effect has been found using speed words and duration estimates (Zhang et al., 2014). Here participants had to decide whether the duration of a presented speed word was closer to 400ms or 1200ms. Fast words were perceived as longer than slow words when the actual duration of the presented word was 800ms, but not at other comparison durations: 800ms is exactly halfway between 400 and 1200ms and therefore reflects the most difficult condition of the experiment. Research in other fields, such as speech perception, also support the idea that perception is more easily influenced by other information in ambiguous or uncertain situations (Sumby & Pollock, 1954; Erber, 1969; Ma et al., 2009; Erber, 1969; Senkowski et al., 2011).

9.2.4.4 Linguistic type

Another form of context that could affect simulation is linguistic type. Differences in simulations for words and sentences might be expected. For example, simulations for single words may not be strong enough to affect sensorimotor processes and instead a larger simulation of an event, as used in sentence comprehension, may be necessary (Bergen et al., 2007). Alternatively, information given in sentences may be too specific and could constrain simulations in such a way that any general simulation effects would be washed out (Meteyard, 2008). Although direct comparisons were not made here, results of the present thesis seem to be similar for words and sentences. That is, evidence for the simulation of speed was observed using both single words and sentences in more (Chapter 5 and 7) and less passive comprehension (Chapter 4 and 6). Although a visual speed condition comparable to Experiment 4 of Chapter 4 was not included with sentences in Chapter 6, results using auditory speed (footsteps sounds) suggest an interference effect with both words and sentences that describe full body actions. Results from Chapter 6 and Chapter 7 suggest however that there may be a difference between speed as encoded in verbs and speed as encoded in adverbs (described above in Section 9.1.4 in more detail).

9.2.4.5 Facilitation versus interference

Context also plays a role in the nature of simulations in terms of the direction of effects. As discussed in section 2.4 of Chapter 2, interactions between language and sensorimotor information have been shown to result in both facilitation in processing and interference and the reasons for the differences are not always clear in the literature. In the present investigation both interference and facilitation effects have been observed (see Table 9-1). In a lexical decision task (Chapter 4), when speed verbs were presented verbally after an auditory speed stimulus, an interference effect was observed in response time. When speed verbs were presented visually after a visual speed stimulus, a facilitation effect was observed. Some potential explanations for the differences exist in the literature. Kaschak et al. (2005) propose the concept of intergratability whereby interference occurs when two stimuli are difficult to integrate into a single event. For example, black and white moving lines would be

Table 9-1. Summary of interference and facilitation effects found in the thesis investigation. An effect in italics reflects a marginally significant effect.

Experiment	**Language stimuli**	**Perceptual modality**	**Perceptual stimulus**	**Verbal modality**	**Effect**
5-4	Verbs	Visual	Moving lines (vection)	Visual	Facilitation (response time)
5-8	Verbs	Auditory	Footsteps	Auditory	Interference (response time)
7-1	Hand/arm sentences	Auditory	Footsteps	Visual	Facilitation (accuracy)
7-1	Full-body sentences	Auditory	Footsteps	Visual	Interference (accuracy)
7-1	Abstract sentences with adverbs	Auditory	Footsteps	Visual	Facilitation (accuracy)
7-1	Concrete sentences with adverbs	Auditory	Footsteps	Visual	Facilitation (accuracy)
7-2	Full-body sentences	Motor	Movement task	Visual	Facilitation (accuracy)

more difficult to integrate with a simulation of a moving car than an image of a moving car would be. However, when looking at the type of perceptual speed stimuli used in Chapter 4, from this perspective an interference effect with the visual stimuli would be predicted because they are less integratable with the speed verbs (as they are simple moving lines) than the auditory stimuli, which are actual real-world sounds that reflect the meaning of the verbs. There are two other potential explanations that are more plausible. The first is that speed simulations could be dominated by visual information and hence when the words and speed stimuli are presented visually this match facilitates processing compared to when presented auditorily. This idea reflects the attentional facilitation effects for visual or auditory dominated words in Connell & Lynott (2014) as described above. The second explanation is that the footsteps sounds are emotional stimuli and emotion may lead to greater simulation due to its close link with the body. This greater simulation results in more competition between speed stimuli and verbal stimuli creating an interference effect. Although both of these explanations seem plausible, they cannot be applied to the present results because both interference and facilitation effects were found with the same speed stimulus (footsteps sounds) with linguistic stimuli of the same modality (spoken sentences) in Chapter 6. When the sound of footsteps was combined with spoken sentences describing actions with the full-body interference effects were observed (consistent with the finding of Chapter 4). But when the sound of footsteps was combined with spoken sentences describing actions with the hands/arms a facilitation effect was found. Adding sentences describing actions with the hands/arms therefore aided in understanding these effects. The most likely explanation for the direction of effects, as described above, is feature overlap. When fast and slow auditory footsteps are combined with words and sentences describing fast and slow actions with the whole body (e.g. *run*, *amble*) interference results because the two stimuli completely overlap: they match in terms of speed and type of effector use in the action (feet). When fast and slow footsteps are instead combined with words and sentences describing fast and slow actions with the hands/arms (e.g. *grab*, *stroke*) facilitation results because there is only partial overlap between the two stimuli: they match only in terms of speed but not in type of effector used (feet versus hands/arms). This effect could also be described as an effect of integratability but in the opposite direction as that described in Kaschak et al (2005): when two events are integratable (e.g. the sound of footsteps and language describing actions that would produce the sound of footsteps) then interference is likely to occur because they are competing for the same resources. This greater overlap in features could also be explained as greater competition for attentional resources (Connell & Lynott, 2012b).

9.2.4.6 Visual context

Finally, the visual context in which the language is comprehended is also important for how simulations develop. As demonstrated in previous studies of 'real-world' language comprehension, information currently available in the environment is extracted and used online in language comprehension (e.g. Altmann & Kamide, 1999). In Chapter 7 I find that the presence of a distractor object in a supporting visual scene modifies the speed simulation to a spoken sentence. When presented with a spoken sentence and a scene containing the agent of the sentence, the target destination and a distractor destination, speed simulation is either hindered, or it is evidenced in longer looks towards the agent for sentences describing slow motion compared to sentences describing fast motion. When there is no distractor present in the scene the difference between sentences describing fast and slow motion is found instead in looks to the target destination. Thus, the simulation process uses any relevant information currently available the context to build a sufficient simulation.

9.2.4.7 Continuum of embodiment

As described in Chapter 1, embodied theories have been placed on a continuum from disembodied to fully embodied. Where do the current results fall along this continuum? It is clear that neither extreme versions account for the present findings. Throughout the thesis I have consistently provided evidence for the mental simulation of speed of motion, thus there must be some role for sensory and motor information in language comprehension. Additionally, that patients with Parkinson's disease were able to sufficiently comprehend sentences and words describing actions and speed, suggests that comprehension is not completely dependent on sensory and motor information. Thus, the results of the thesis support a theory somewhere between secondary and weak embodiment. Further work would be required to determine whether sensory and motor simulation observed here plays a fundamental role, or is rather due to secondary activation. This could involve the use of more fine-grained temporal measures, such as EEG. However, it should be noted, that a more fruitful research venture now is to further examine the nature and functions of mental simulations, rather than arguing for or against a particular view, as described below in section 9.4.

9.3 Overarching implications of the work

Thus, the main theoretical implications from the thesis are:

1. Simulations involve fine-grained features of events such as speed and include information from vision, audition and action.

2. Simulations are dynamic. They are built on the fly and are dependent on and interact with contextual factors.

3. Simulations of speed are body-related in that the motion of a specific agent is simulated. These body-relevant simulations can include specific details such as the effector implicated in an action.

9.4 The way forward

It is clear from the present results that the effect of context is of great importance to embodied theories in terms of when simulations are used in comprehension and what the nature of these simulations are. Further work is needed to clearly define the contextual factors that affect simulation and when and how they come into play.

One avenue for an investigation of context would be to compare simulations between reading and listening. Listening typically occurs in a social environment with an interlocutor. This means there is often a large amount of noise and contextual information and as a listener one needs to be prepared to act, be it making a verbal or action response. When reading however, most often the greater goal is to build a representation of the text and not necessarily respond in any way at all (at least not immediately). Therefore, when listening there will be multiple perceptual and action processes occurring due to environmental factors, whereas when reading there is little additional perceptual or action processes other than those in response to reading itself. Labruna, Fernández-del-Olmo, Landau, Duqué and Ivry (2011) found increased MEP activity after TMS to the left premotor cortex for action words compared to control words but only when the words were presented visually and not auditorily. They speculated that this difference might be due to stronger links between sensorimotor information and language in reading compared to listening because of the longer learning process for reading compared to listening, for which real-world referents and actions towards them are mapped to words and sentences. However it could be that simulation during reading is easier due the lack of concurrent environmental information typically occurring in the comprehension situation.

The results in the present thesis suggest that speed simulation may be occurring at a different level of processing compared to simulation of other dimensions, such as direction: Meteyard et al. (2009) and Pavan et al. (2012) found that direction words affected perceptual sensitivity in a motion detection task but in Chapter 5 I did not find evidence that speed words affect perceptual sensitivity but perceived speed (a level of perceptual decision) in a speed discrimination task. There may also be a difference in terms of necessity of speed simulation in comprehension compared to other dimensions. For example, in Chapter 8, results suggest that Parkinson's patients are not impaired in implicitly processing speed information, but work elsewhere has shown that they are for action information more generally (Fernandino et al. 2013). Thus speed may not be a crucial component to the meaning of the words used in the thesis unless comprehension is specifically oriented to the speed dimension or if a deep level of processing is possible. It might be possible therefore that there is a hierarchy of domains in terms of which are necessarily simulated, or more easily simulated, and those that are instead more superfluous, providing a richer simulation dependent on context or comprehension goals. This hierarchy might reflect the salience and frequency of these domains in our real world interactions: just as not all aspects of the environment are processed or attended to, not every feature of a described referent or an event is necessarily simulated. For example, in simulating an object salient features such as size and colour may be more necessarily simulated than a less important feature such as texture. There are of course a number of differences in both the tasks and stimuli utilized between the work presented here and the work that has addressed other dimensions, thus the above description is at present only speculative. A more controlled investigation of simulations of different domains would be required to investigate this idea.

One obvious direction for embodied research to take is to move into more real-world experimental settings. It is possible that within experimental conditions in which the stimuli and situation are carefully designed and controlled, and when responses are averaged over many trials, evidence for simulation is found. However, it is unclear to what extent the same simulations are used during real-world interactions in which we are presented with lots of information, in noisy environments and in which multiple responses are required. A first step would be to move away from single words and sentences out of context towards longer discourse. As described earlier, longer discourse provides the opportunity for meaning to build up and for more elaborate simulations to develop. Studies are beginning to find evidence for mental simulation during comprehension of discourse, including discourse taken from real books and not designed for the purpose of eliciting specific simulations (e.g. Kurby & Zacks, 2013).

To more accurately reflect comprehension in the real world, further perceptual modalities and their interactions could be investigated. At present studies of simulation mainly focus on visual, auditory and action information but our experience in the world is much richer than this. As discussed in Chapter 4, simulations during language comprehension should reflect the multimodal experiences of the world, and should therefore include the less-studied senses including tactile perception, olfaction and taste. It would be interesting to investigate to what extent each modality is represented in particular concepts, if particular modalities dominate and whether this changes depending on context (e.g. Hoenig et al 2008). Further, research has suggested that there are crossmodal correspondences between perceptual modalities (e.g. Dolscheid, Shayan, Majid, & Casasanto 2013), which could affect the nature of multimodal simulations. It would therefore also be fruitful to investigate simulation in comprehension of language that suggests crossmodal correspondences and their interaction with modal information present in the environment. Investigating the meaning of words in terms of their multimodal composition may in fact be the most fruitful direction to take. Recent research suggests that defining words in terms of their perceptual strength and perceptual dominance may be most advantageous for language research as such measures more accurately reflect the comprehension process than other descriptions of words such as semantic similarity and lexical association (Connell & Lynott, 2012a).

Finally, if the presence and nature of simulations varies so much depending on contextual factors then the implications of this variability needs to be addressed. There is likely to be comprehension consequences for simulation versus no simulation. For example, when there is less simulation the probability of misinterpretation may be increased because linguistic associations will be relied upon more, which are viewed as “quick and dirty” shortcuts. For example, based on associations between a few key words in a sentence a comprehender might predict an interpretation that is in fact incorrect. Comprehension with less simulation may also reduce or alter the memory for sentence content because the representation of the meaning is less rich so there is less context for memory retrieval. On the other hand, greater simulation may lead to false memories for features that are common to a particular simulation. For example, in a famous study by Loftus and Palmer (1974), after participants had viewed a video of a car accident, they recalled that the car was moving faster and were more likely to report that there was broken glass at the scene when the car accident was described with the verb *smashed* compared to other verbs that suggested less impact such as *collided.*

9.5 Conclusion

The work contained in this thesis has provided evidence for the simulation of speed in both word and sentence comprehension. The findings suggest that speed simulations contain visual, auditory and action information. Speed simulations do not reflect speed in an abstracted way but reflect speed in terms of an agent in action and can code specific information such as the effector involved in the action. This is reflected in the finding that interactions between speed in language and visual speed occur at levels of perceptual decision and not perceptual sensitivity. Based on the patterns found in the comprehension of speed language in patients with Parkinson's disease, speed simulation may not be critical to comprehension of language describing fast and slow actions at all levels of processing. At shallow or implicit levels of processing only action simulations in general may be necessary whilst speed information is more crucial for deep and explicit processing. As with other embodied findings within the literature, speed simulations is highly dependent on contextual factors. The specific details and comprehension consequences of these contextual effects needs to be determined in further investigations.

Appendix 1. Norming and matching data

Table Appendix 1-1. Slow verbs used in Chapters 4, 5 and 7

Verb	Mean Speed Rating	Mode Speed Rating
ambled	2.39	2
crawled	1.45	1
dallied	2.05	2
dawdled	1.68	1
meandered	2.35	2
plodded	2.15	1
rambled	3.05	2
roamed	2.75	2
sauntered	2.75	2
shuffled	2.9	3
sneaked	2	1
strolled	2.6	3
tiptoed	1.4	1
traipsed	2.9	2
trudged	2.05	1
wandered	1.8	1

Table Appendix 1-2. Fast verbs used in Chapters 4, 5 and 7

Verb	Mean Speed Rating	Mode Speed Rating
bolted	6.4	7
charged	5.95	6
darted	6	7
dashed	6	6
galloped	5.6	6
hurried	5.6	6
raced	6.3	7
raged	5.5	7
ran	5.8	6
rushed	5.96	6
shot	6.1	7
sped	6.25	6
sprinted	6.7	7
stormed	5.79	6
zipped	5.65	6
zoomed	6.1	7

Table Appendix 1-3. Neutral verbs used in Chapters 5 and 7

Verb	Mean Speed Rating	Mode Speed Rating
advanced	4	2
bounded	4.65	5
clambered	3.2	2
coasted	3.4	3
cruised	3.65	3
fell	4.85	5
hastened	4.6	5
hopped	3.75	4
jogged	4.65	5
jumped	4.65	5
marched	3.95	4
moved	3.53	4
paced	3.85	3
paraded	3	3
pranced	4.2	4
scampered	4.8	5
shifted	3.05	3
skipped	4.15	5
slid	4.05	5
stamped	3.6	2
strode	3.9	3
strutted	3.6	4
travelled	3.9	4
trotted	3.2	3
walked	3.45	4

Table Appendix 1-4. Slow adverbs used in Chapter 7, Experiment 7-4

Verb	Mean Speed Rating	Mode Speed Rating
slowly	1.4	1
lazily	1.5	2.5
sluggishly	1.6	1
sleepily	1.7	1
reluctantly	2	2
cautiously	2.4	2
idly	2.6	3
carefully	2.8	3
gently	2.8	3
gradually	2.8	3
leisurely	2.8	3
listlessly	2.89	2
calmly	3.1	3
casually	3.2	3

Table Appendix 1-5. Fast adverbs used in Chapter 7, Experiment 7-4

Verb	Mean Speed Rating	Mode Speed Rating
readily	4.9	5
actively	5.3	5
abruptly	5.5	5.5
briskly	5.5	6
promptly	5.6	5
immediately	5.8	7
hastily	6	6
swiftly	6	6
quickly	6.1	6
suddenly	6.2	7
speedily	6.3	7
hurriedly	6.4	6
rapidly	6.4	6
frantically	6.8	7

Table Appendix 1-6. Full-body verbs matched for Chapter 6

Slow Verbs	Fast Verbs	Abstract Verbs
sneaked	stormed	mourned
floated	hurried	ensured
drifted	shifted	admired
crawled	skipped	shocked
stepped	stamped	pleased
plodded	flitted	fancied
roamed	zoomed	joked
rambled	darted	meddled
tiptoed	trotted	scolded
sauntered	scampered	professed
climbed	sprang	dreamt
strolled	scurried	forgave
wandered	plunged	deceived
shuffled	bolted	insured

Table 1-7. Lexical variables (mean and standard deviation) and p-values from ANOVA with word type as factor for matched full-body verbs in Chapter 6. All lexical measures taken from the English Lexicon Project (http://elexicon.wustl.edu/)

	Slow full body actions	**Fast full body actions**	**Abstract actions**	**p-value**
Length	7.29 (0.73)	6.93 (0.83)	7 (0.88)	0.07
Log frequency	6.12 (1.47)	6.12 (1.32)	6.56 (1.32)	0.09
Ortho neighbour	2.57 (1.45)	2.79 (1.58)	2.86 (1.46)	0.32
Phonemes	5.57 (0.76)	5.71 (0.73)	5.5 (0.94)	0.51
Syllables	1.57 (0.51)	1.57 (0.51)	1.64 (0.5)	0.62

Table Appendix 1-8. Hand/arm verbs matched for Chapter 6

Slow hand actions	Fast hand actions	Abstract actions
brushed	yanked	spared
caressed	snatched	disliked
cradled	whacked	doubted
grazed	swung	regretted
handled	punched	feared
held	hit	lost
hugged	hurled	obeyed
moved	struck	hoped
rolled	shoved	scared
stroked	smacked	owed
touched	slapped	ruled

Table 1-9. Lexical variables (mean and standard deviation) and p-values from ANOVA with word type as factor for matched hand/arm verbs in Chapter 6. All lexical measures taken from the English Lexicon Project (http://elexicon.wustl.edu/)

	Slow hand actions	**Fast hand actions**	**Abstract actions**	**p-value**
Length	6.36 (1.12)	6.18 (1.33)	6 (1.55)	0.69
Log frequency	7.95 (1.88)	7.43 (1.46)	7.89 (1.41)	0.15
Ortho neighbour	5 (3.54)	5.73 (4.84)	5.55 (5.09)	0.88
Phonemes	4.91 (0.94)	4.54 (0.69)	4.73 (1.62)	0.74
Syllables	1.27 (0.47)	1 (0)	1.45 (0.69)	0.08

Table Appendix 1-10. Adverbs matched for Chapter 6 and sentences in Chapter 8

Slow Adverbs	Fast Adverbs	Abstract Adverbs
awkwardly	speedily	usefully
patiently	urgently	knowingly
leisurely	fiercely	normally
intently	abruptly	loosely
gradually	efficiently	officially
carefully	eagerly	certainly
vaguely	quickly	genuinely
calmly	keenly	sensibly
reluctantly	frantically	voluntarily
slowly	actively	openly
painfully	rapidly	evidently
casually	suddenly	clearly
cautiously	comfortably	customarily

Table Appendix 1-11. Lexical variables (mean and standard deviation) and p-values from ANOVA with word type as factor for matched adverbs used in sentences in Chapter 6 and Chapter 8. All lexical measures taken from the English Lexicon Project (http://elexicon.wustl.edu/)

	Slow Adverbs	**Fast Adverbs**	**Abstract Adverbs**	**p-value**
Length	8.46 (1.45)	8.31 (1.65)	8.62 (1.5)	0.68
Log frequency	7.52 (1.33)	7.81 (1.53)	8.13 (1.79)	0.31
Ortho neighbour	0.23 (0.44)	0.23 (0.44)	0.38 (0.65)	0.63
Phonemes	6.77 (1.64)	7 (1.47)	7.23 (2)	0.67
Syllables	2.85 (0.55)	2.92 (0.64)	3.38 (0.65)	0.08
LD RT	716 (91)	736 (91)	724 (88)	0.79
LD Acc	0.97 (0.03)	0.95 (0.06)	0.98 (.03)	0.17
Naming RT	673 (42)	681 (57)	688 (74)	0.79

Table Appendix 1-12. Concrete and abstract verbs matched for adverb sentences in Chapter 6 and Chapter 8

Concrete Verbs	Abstract Verbs	Abstract-Abstract Verbs
rolled	thought	acquired
pressed	checked	admired
pulled	complied	boasted
grasped	considered	claimed
picked	figured	expressed
lifted	rated	joked
tapped	pondered	loved
twisted	mused	planned
knocked	worked	selected
twirled	debated	tested
took	saw	trusted
threw	wished	upset
raised	reasoned	won

Table Appendix 1-13. Lexical variables (mean and standard deviation) and p-values from ANOVA with word type as factor for matched concrete and abstract verbs for adverb sentences in Chapter 6 and Chapter 8. All lexical measures taken from the English Lexicon Project (http://elexicon.wustl.edu/)

	Concrete Verbs	**Abstract Speed Verbs**	**Abstract-Abstract Verbs**	***p*-value**
Length	6.15 (0.9)	6.69 (1.75)	6.31 (1.89)	0.66
Log frequency	8.72 (1.66)	8.96 (2.07)	9.85 (1.6)	0.3
Ortho neighbour	5.85 (4.74)	5.07 (5.94)	6.3 (7.43)	0.87
Phonemes	4.54 (1.2)	5.07 (1.71)	5.46 (1.56)	0.4
Syllables	1.15 (0.38)	1.69 (0.75)	1.69 (0.63)	0.09
LD RT	647 (58)	678 (67)	649 (52)	0.4
LD Acc	0.96 (0.03)	0.97 (0.03)	0.97 (0.03)	0.68
Naming RT	621 (47)	648 (58)	624 (46)	0.36
Valence	5.57 (.18)	5.88 (.23)	5.92 (.45)	0.13

Table 1-14. Full-body verbs matched for lexical decision task in Chapter 8

Slow verbs	Fast verbs	Abstract verbs
to roam	to whiz	to profess
to tarry	to stamp	to allot
to ramble	to hasten	to sublet
to float	to zoom	to broach
to trek	to advance	to claim
to climb	to cruise	to induce
to shuffle	to hurry	to permit
to trudge	to flit	to yearn
to sneak	to glide	to inspect
to stroll	to jog	to waive
to crawl	to sprint	to reign
to wander	to dash	to obey
to meander	to bolt	to insure
to slink	to stride	to vow
to tiptoe	to hurtle	to exhort
to plod	to dart	to conceive

Table 1-15. Lexical variables (mean and standard deviations) and p-values from ANOVA with word type as factor for matched full-body verbs used in lexical decision task Chapter 8. All lexical measures taken from the English Lexicon Project (http://elexicon.wustl.edu/)

	Slow verbs	Fast Verbs	Abstract Verbs	p-value
Length	5.38 (0.96)	4.94 (1.12)	5.63 (1.2)	0.28
Log frequency	6.8 (1.71)	7.57 (1.74)	7.04 (1.73)	0.14
Ortho neighbour	3.75 (3.3)	5.69 (4.74)	2.5 (4.32)	0.11
Phonemes	4.38 (0.72)	4.19 (0.91)	4.5 (1.46)	0.75
Syllables	1.44 (0.63)	1.25 (0.44)	1.63 (0.5)	0.06
LD RT	703 (96)	649 (74)	708 (79)	0.09
LD Acc	0.84 (0.18)	0.93 (0.13)	0.9 (0.1)	0.24
Naming RT	664 (57)	632 (46)	673 (63)	0.12

Table Appendix 1-16. Mean and standard deviations of lexical measures for matched full-body verbs and pseudo-verbs for lexical decision task in Chapter 8 and p-values from t-test. All lexical measures taken from the English Lexicon Project (http://elexicon.wustl.edu/)

	Speed verbs	Pseudowords	p-value
Length	5.41 (0.94)	5.41 (0.94)	Perfect match
Ortho neighbour	3.29 (2.64)	3.27 (2.62)	Perfect match
LD RT	679 (78)	702 (69)	0.08
LD Acc	0.92 (0.09)	0.92 (0.1)	0.81

Table Appendix 1-17. Arm/hand verbs matched for lexical decision task in Chapter 8

Slow verbs	Fast verbs	Abstract verbs
to brush	to yank	to know
to caress	to snatch	to plan
to cradle	to whack	to muse
to graze	to swing	to ponder
to handle	to punch	to infer
to hold	to hit	to deduct
to hug	to hurl	to choose
to move	to strike	to think
to roll	to shove	to judge
to stroke	to smack	to reflect
to touch	to slap	to wonder

Table Appendix 1-18. Mean and standard deviations of lexical measures and p-values from ANOVA with word type as factor for matched hand/arm verbs used in lexical decision task in Chapter 8. All lexical measures taken from the English Lexicon Project (http://elexicon.wustl.edu/)

	Slow verbs	**Fast Verbs**	**Abstract Verbs**	**p-value**
Length	4.91 (1.04)	4.73 (0.9)	5.27 (1)	0.46
Log frequency	9 (1.9)	8.18 (1.42)	9.85 (2.41)	0.13
Ortho neighbour	7.18 (6.54)	7.09 (5.17)	4.55 (3.14)	0.27
Phonemes	4 (0.89)	3.82 (0.6)	4.27 (1.4)	0.53
Syllables	1.27 (0.47)	1(0)	1.45 (0.52)	0.06
LD RT	619 (54)	648 (67)	639 (67)	0.63
LD Acc	0.98 (0.03)	0.96 (0.04)	0.97 (0.05)	0.62
Naming RT	599 (60)	623 (47)	615 (41)	0.56

Table Appendix 1-19. Mean and standard deviations of lexical measures and p-values from t-test for matched hand/arms verbs and pseudo-verbs in lexical decision task in Chapter 8. All lexical measures taken from the English Lexicon Project (http://elexicon.wustl.edu/)

	Speed verbs	Pseudo-words	p-value
Length	4.97 (0.98)	4.7 (0.98)	0.24
Ortho neighbour	4.42 (3.34)	6.27 (5.13)	0.06
LD RT	660 (43)	635 (62)	0.07
LD Acc	0.97 (0.25)	0.97 (0.03)	0.99

Table Appendix 1-20. Adverbs matched for lexical decision

Slow Adverbs	Fast Adverbs	Abstract Adverbs
awkwardly	speedily	earnestly
patiently	urgently	magically
delicately	impatiently	offensively
leisurely	fiercely	ethically
intently	abruptly	stupidly
gradually	efficiently	financially
carefully	quickly	greatly
lazily	briskly	cruelly
vaguely	eagerly	proudly
calmly	keenly	rudely
sleepily	skilfully	helpfully
reluctantly	frantically	spiritually
gently	boldly	kindly
limply	nimbly	bravely
slowly	actively	hopefully
sluggishly	hurriedly	uselessly
painfully	rapidly	morally
casually	suddenly	terribly
cautiously	comfortably	miserably
listlessly	alertly	boastfully

Table Appendix 1-21. Mean and standard deviations of lexical measures and p-values from ANOVA with word type as factor for matched adverbs in lexical decision in Chapter 8. All lexical measures taken from the English Lexicon Project (http://elexicon.wustl.edu/)

	Slow Verbs	**Fast Verbs**	**Abstract Verbs**	**p-value**
Length	8.3 (1.63)	8.2 (1.35)	8.45 (1.57)	0.62
Log frequency	6.7 (1.93)	6.89 (1.97)	6.87 (1.98)	0.74
Ortho neighbour	0.4 (0.68)	0.4 (0.68)	0.4 (0.68)	Perfect match
Phonemes	6.95 (1.54)	6.95 (1.32)	6.95 (1.23)	.96
Syllables	2.85 (0.59)	2.85(0.67)	2.85 (0.67)	.9
LD RT	731 (97)	748 (85)	726 (85)	0.56
LD Acc	0.95 (0.08)	0.92 (0.08)	0.96 (.03)	0.07
Naming RT	685 (50)	690 (57)	695 (63)	0.89

Table Appendix 1-22. Mean and standard deviations of lexical measures for and p-values from t-test matched adverbs and pseudo-adverbs in lexical decision task in Chapter 8. All lexical measures taken from the English Lexicon Project (http://elexicon.wustl.edu/)

	Adverbs	Pseudo-adverbs	t-test p-value
Length	8.32 (1.62)	8.5 (1.65)	0.28
Ortho neighbour	0.4 (0.67)	0.37 (0.64)	0.42
LD RT	735 (88)	739 (82)	0.76
LD Acc	0.94 (0.07)	0.95 (0.8)	0.62

Table Appendix 1-23. First set of verbs for semantic similarity judgments in Chapter 8.

Slow Verbs	Fast Verbs	Positive Verbs	Negative Verbs
to sneak	to glide	to thrive	to riot
to step	to jump	to plan	to blame
to ramble	to hasten	to inspire	to deceive
to float	to stamp	to fancy	to cheat
to trek	to storm	to trust	to argue
to climb	to cruise	to assure	to upset
to drift	to plunge	to admire	to spoil
to shuffle	to hurry	to unite	to annoy
to crawl	to sprint	to mentor	to regret
to wander	to leap	to joke	to scare

Table Appendix 1-24. Mean and standard deviations of lexical measures and p-values from ANOVA with word type as factor for matched verbs in pilot semantic similarity judgments of Chapter 8. All lexical measures taken from the English Lexicon Project (http://elexicon.wustl.edu/)

	Slow Verbs	Fast Verbs	Positive Verbs	Negative Verbs	p-value
Length	5.2 (0.92)	5.2 (0.79)	5.33 (0.94)	5.2 (0.79)	0.89
Log frequency	8.4 (1.24)	8.39 (1.22)	8.75 (1.24)	8.53 (0.94)	0.3
Ortho neighbour	3.6 (3.13)	3.6 (3.03)	2.8 (2.99)	2.7 (3.56)	0.08
Phonemes	4.3 (0.48)	4.4 (0.84)	4.7 (0.9)	4.3 (0.95)	0.56
Syllables	1.3 (0.48)	1.2 (0.42)	1.6 (0.49)	1.5 (0.53)	0.1
LD RT	643 (86)	639 (71)	649 (51)	662 (65)	0.89
LD Acc	0.95 (0.06)	0.97 (0.04)	0.98 (0.02)	0.98(.02)	0.13
Naming RT	647 (49)	627 (44)	613 (47)	637 (53)	0.62

Table Appendix 1-25. Final set of verbs matched for semantic similarity judgments

Slow	Static1	Fast	Static 2	Negative	Positive	Thinking	Seeing
to shuffle	to suspend	to whack	to sprawl	to deceive	to inspire	to presume	to inspect
to step	to stay	to throw	to sit	to lose	to save	to plan	to spot
to carry	to lie	to shoot	to sleep	to blame	to trust	to judge	to watch
to hug	to pose	to dash	to halt	to riot	to dare	to muse	to peer
to wander	to retire	to shove	to kneel	to regret	to admire	to ponder	to detect
to feel	to stop	to race	to rest	to fear	to plan	to guess	to look
to brush	to squat	to hurry	to relax	to annoy	to fancy	to infer	to attend
to sneak	to desist	to smack	to lounge	to spoil	to thrive	to deduct	to glance
to roll	to cease	to bound	to pause	to shock	to dream	to choose	to stare
to handle	to remain	to charge	to stand	to forget	to manage	to think	to survey
to stroke	to settle	to advance	to hesitate	to dislike	to deserve	to reflect	to witness
to trek	to stall	to grab	to still	to lie	to care	to know	to eye
to roam	to freeze	to swing	to finish	to suffer	to assure	to decide	to regard
to crawl	to wait	to slap	to delay	to fail	to joke	to solve	to scan
to caress	to recline	to sprint	to repose	to confuse	to delight	to appraise	to observe
to ramble	to perch	to snatch	to poise	to boast	to unite	to assess	to glare

Table Appendix 1-26. Mean and standard deviations of lexical measures and p-values from ANOVA with word type as factor for final matched verbs in semantic similarity judgments of Chapter 8. All lexical measures taken from the English Lexicon Project (http://elexicon.wustl.edu/)

	Fast verbs	Static verbs 1	Slow verbs	Static verbs 2	Thinking verbs	Seeing verbs	Positive verbs	Negative verbs	*p*-value
Length	5.06 (0.85)	5.19 (1.11)	5 (1.09)	5.19 (1.22)	5.56 (1.15)	5.31 (1.25)	5.31 (1.14)	5.19 (1.22)	0.17
Log frequency	8.93 (1.38)	8.8 (2.05)	8.86 (1.62)	8.94 (1.23)	9.43 (2.4)	9.24 (1.41)	9.29 (1.37)	8.94 (1.23)	0.12
Ortho neighbour	5.56 (4.49)	5.06 (6.35)	6.06 (5.11)	6.06 (6.17)	3.19 (3.17)	5.63 (5)	6.31 (8.48)	6.06 (6.17)	0.51
Phonemes	3.93 (0.93)	4.31 (1.13)	4.06 (0.77)	4.13 (1.36)	4.31 (1.3)	4.37 (1.5)	4.31 (0.95)	4.13 (1.36)	0.83
Syllables	1.13 (0.34)	1.38 (0.62)	1.38 (0.5)	1.44 (0.51)	1.5 (0.52)	1.44 (0.51)	1.5 (0.52)	1.44 (0.51)	0.14
LD RT	621 (44)	636 (72)	652 (79)	637 (49)	645 (65)	629 (54)	630 (46)	637 (49)	0.15
LD Acc	0.97 (0.07)	0.96 (0.06)	0.96 (0.05)	0.99 (0.02)	0.96 (0.05)	0.96 (0.03)	0.98 (0.03)	0.99 (0.02)	0.31
Naming RT	621 (44)	627 (56)	634 (62)	623 (51)	629 (40)	622 (57)	617 (41)	623 (51)	0.77

Appendix 2. Sentences

A2.1. Chapter 6 sentences

A2.1.1. Hand sentences

Sentence	**Type**
The man brushed the dust away.	slow
Lucy caressed the small kitten in the basket.	slow
Tim cradled the baby in his arms.	slow
Shaun grazed his arm against the wall.	slow
The worker handled the packages that were ready.	slow
The vet held the dog in his hands.	slow
Tonya hugged the pillow that was on the bed.	slow
Jake moved the box sitting before him.	slow
Tom rolled the keg towards the doorway.	slow
Amy stroked her chin as she tried to remember.	slow
Jill touched her friend’s arm.	slow
The man yanked the door open.	fast
Mark snatched the last cookie from the table.	fast
Jim whacked the wasp in his room.	fast
Dave swung his bat towards the ball.	fast
The boxer punched the opponent that was opposite.	fast
The golfer hit the ball with the club.	fast
Katie hurled the frisbee that was on the floor.	fast
Matt struck the ball coming towards him.	fast
Rick shoved the nag behind the cupboard.	fast
Sarah smacked her head when she started to forget.	fast
Kelly slapped the man’s face.	fast

The man spared the bad news.	abstract
Frank disliked the new girl from the city.	abstract
Luke doubted the story from his friend.	abstract
Zack regretted his choice over the colour.	abstract
The student feared the news that was coming.	abstract
The actor lost the drive for his success.	abstract
Freddy obeyed the rules that he had been given.	abstract
Dale hoped the job lasted all summer.	abstract
Ross scared the cat beneath the table.	abstract
Sandy owed her friend after she looked after her.	abstract
Olly ruled the town's team.	abstract
The man built the old warmth.	nonsense
Ray chaired the circus from the sun.	nonsense
Drew developed the army from his romance.	nonsense
Jordan located his rumour in the space.	nonsense
The frog installed the pan in the joy.	nonsense
The chef secured the luck in the station.	nonsense
Ethan shrank the sea that he had heard.	nonsense
Michelle sold the peace at last.	nonsense
Julie repaired the ant in the tree.	nonsense
Molly displayed her rock in the star around her.	nonsense
Diane framed the zoo's rain.	nonsense
The girl hosted the thunder hole.	nonsense
Erica dug the lake for the monkey.	nonsense
Rose ripped the water from the brick.	nonsense
Jesse tore the clock in the fruit.	nonsense
The bear slid the soup into the thought.	nonsense
The teacher carried the wealth in the forest.	nonsense
Antony scratched the sand that he had sung.	nonsense
Tony knelt the room for dinner.	nonsense

Blake sat the pride in the store.	nonsense
Ryan passed his sleep to the mind above him.	nonsense
Brendan cupped the day's hurt.	nonsense
The boy fastened the water rage.	nonsense
Martin hauled the trust from the bird.	nonsense
Harry deleted the box from the fear.	nonsense
Jim dived the bridge in the floor.	nonsense
The dog swiped the tin the party.	nonsense
The player stopped the skill in the balloon.	nonsense
Neil removed the fuss that had been swallowed.	nonsense
Terry drove the chicken to night.	nonsense
Lee disguised the fish in the bush.	nonsense
Fish buzzed their thoughts to the bottom of time.	nonsense
Sam hovered around the wild ear.	nonsense

A2.1.2. Full-body sentences

Sentence	**Type**
The professor sneaked down the corridor.	slow
The school girl floated along the hallway.	slow
Sarah drifted away from the table.	slow
The toddler crawled towards her mother.	slow
The manager stepped into the office.	slow
Liz plodded to the other side of the room.	slow
The young boy roamed through the lanes.	slow
Daniel rambled through the forest.	slow
The kid tiptoed down the stairs.	slow
Mary sauntered away from the scene.	slow
Jack climbed over the rocks.	slow
The old lady strolled across the road.	slow
Sally wandered forward into the waves	slow

Chris shuffled out of the classroom.	slow
The professor stormed down the corridor.	fast
The school girl hurried along the hallway.	fast
Sarah shifted away from the table.	fast
The toddler skipped towards her mother.	fast
The manager stamped into the office.	fast
Liz flitted to the other side of the room.	fast
The young boy zoomed through the lanes.	fast
Daniel darted through the forest.	fast
The kid trotted down the stairs.	fast
Mary scampered away from the scene.	fast
Jack sprang over the rocks.	fast
The old lady scurried across the road.	fast
Sally plunged forward into the waves.	fast
Chris bolted out of the classroom.	fast
The brother mourned his recent loss.	abstract
The office worker ensured his new promotion.	abstract
Sophie admired her old history teacher.	abstract
The performer shocked the large crowd.	abstract
The performance pleased the dance examiners.	abstract
Luke fancied a nice Italian meal for his dinner.	abstract
The old clown joked with his audience.	abstract
Marcus meddled in the argument.	abstract
The teacher scolded the chatting children.	abstract
Shane professed his strong opinion openly.	abstract
Zack dreamt of being famous.	abstract
The old man forgave his wife eventually.	abstract
John deceived all of his friends.	abstract
Kirsty insured her brand new car.	abstract
The pilot swam the wooden egg.	nonsense

The bank manager lifted his yellow memories.	nonsense
Steven reached for the floating moon.	nonsense
The swimmer drank around a forest.	nonsense
The captain rolled under the volcano.	nonsense
Laura hindered a large cloud up the side building.	nonsense
The hat altered the city bridge.	nonsense
Mary rejected the flying thoughts.	nonsense
The house caught the falling pigs.	nonsense
Ruth danced the long ship home.	nonsense
James distressed the new leaves.	nonsense
The empty sun moved the green cats.	nonsense
Ben rolled into a sliding star.	nonsense
Julia pinched the country sunbeam.	nonsense
The wife bit the loud speech.	nonsense
The house cat shook the mountain hole.	nonsense
Simone seized the rotating colourful planets.	nonsense
The armchair plotted a broken stunt.	nonsense
The fish wiped away the teardrops.	nonsense
Louise read up a meadow over a dark doorway.	nonsense
The rat pulled the air around.	nonsense
Mike charged along the rocket launch.	nonsense
The staircase bounded towards the seahorse.	nonsense
Rick strolled along the choppy ocean.	nonsense
Paul meandered through the brain.	nonsense
The dusty book chased the door mat.	nonsense
David slogged down the floating balloon.	nonsense
Lucy exercised the quick conversational idea.	nonsense

A2.1.3. Adverb sentences

	Sentence type	Adverb type
Bob speedily thought over the business plan.	abstract	fast
Greg urgently checked the proposal.	abstract	fast
Abby fiercely complied with the rules.	abstract	fast
Sam abruptly considered the act.	abstract	fast
Jimmy efficiently figured out the problem.	abstract	fast
Mick quickly rated all the entries.	abstract	fast
Sherry eagerly pondered the new project.	abstract	fast
Amy keenly mused over the future.	abstract	fast
Carly frantically worked out the question’s answer.	abstract	fast
Will actively debated the quarrel between his friends.	abstract	fast
Bill rapidly saw the flaw in the plot.	abstract	fast
Dean suddenly wished he were in the event.	abstract	fast
Richard comfortably defended the views of his political party.	abstract	fast
Bob awkwardly thought over the business plan.	abstract	slow
Greg patiently checked the proposal.	abstract	slow
Abby leisurely wondered about the course.	abstract	slow
Sam intently considered the act.	abstract	slow
Jimmy gradually figured out the problem.	abstract	slow
Mick carefully rated all the entries.	abstract	slow
Sherry vaguely pondered the new project.	abstract	slow
Amy calmly mused over the future.	abstract	slow
Carly reluctantly worked out the question’s answer.	abstract	slow
Will slowly debated the quarrel between his friends.	abstract	slow
Bill painfully saw the flaw in the plot.	abstract	slow
Dean casually wished he were in the event.	abstract	slow
Richard cautiously defended the views of his political party.	abstract	slow
Max usefully acquired the new clients.	abstract	abstract
Gwen knowingly allowed the breach.	abstract	abstract

Hayley ordinarily boasted about her money.	abstract	abstract
Craig loosely claimed his importance.	abstract	abstract
Simon officially expressed his major concern.	abstract	abstract
Dan certainly joked about the issue.	abstract	abstract
Mary genuinely loved the old songs.	abstract	abstract
Amy positively planned her next step.	abstract	abstract
Dennis voluntarily selected the best drawing entry.	abstract	abstract
Jeff openly tested the ideas for his project.	abstract	abstract
Kurt honestly trusted the man in the car.	abstract	abstract
Kyle clearly upset the girl in the bar.	abstract	abstract
Brian innocently won all the rounds of the quiz.	abstract	abstract
John speedily rolled up the sleeping bag.	concrete	fast
Jane urgently pressed the button	concrete	fast
Gary fiercely pulled back the curtain.	concrete	fast
Ken abruptly grasped the mug.	concrete	fast
Stacey efficiently picked up all the litter.	concrete	fast
Phil quickly lifted up the cake.	concrete	fast
Mary eagerly tapped on the front window.	concrete	fast
Amy keenly twisted open the bottle.	concrete	fast
Katie frantically knocked on the director's door.	concrete	fast
Jamie actively twirled the pencil between his fingers.	concrete	fast
Mike rapidly took the spade out of the ground.	concrete	fast
Mark suddenly threw the ball down the street.	concrete	fast
Graham comfortably raised the sack onto the truck.	concrete	fast
John awkwardly rolled up the sleeping bag.	concrete	slow
Jane patiently pressed the button.	concrete	slow
Gary leisurely pulled back the curtain.	concrete	slow
Ken intently grasped the mug.	concrete	slow
Stacey gradually picked up all the litter.	concrete	slow
Phil carefully lifted up the case.	concrete	slow

Mary vaguely tapped on the front window.	concrete	slow
Amy calmly twisted open the bottle.	concrete	slow
Katie reluctantly knocked on the boss's door.	concrete	slow
James slowly twirled the pencil between his fingers.	concrete	slow
Mike painfully yanked the spade out of the ground.	concrete	slow
Mark casually threw the ball down the street.	concrete	slow
Graham cautiously raised the sack onto the truck.	concrete	slow
June earnestly flew the computer grass.	concrete	slow
Rick listlessly ate an idea.	nonsense	
Jessica offensively flushed out the minds.	nonsense	
Margaret boldly cooked the clouds.	nonsense	
Simon delicately shimmered out the magazine.	nonsense	
Laura dangerously moved around the whispers.	nonsense	
Will alertly jumped the elephant spoon.	nonsense	
Charlotte impatiently slept around the sunshine.	nonsense	
Ben proudly shook over the beach’s oven.	nonsense	
Sarah softly balanced the red sentence between her home.	nonsense	
Steve gently collected the mist in the gloves.	nonsense	
Ellen shakily wrapped the glass over the turtle.	nonsense	
Nick limply cleaned out the rainbow of the pear.	nonsense	
Stewart nimbly washed out the vapour legs.	nonsense	
Rachel accidentally drank the chairs.	nonsense	
Rob affirmatively kicked over the moon.	nonsense	
Alison lazily shone the building.	nonsense	
Marcus hopelessly danced up the bucket.	nonsense	
Barbara briskly wiped away the jungle.	nonsense	
Andy hurriedly opened up the rectangular ocean.	nonsense	
Maria sluggishly ironed out the peas.	nonsense	
Sam passionately brushed up the thunder’s air.	nonsense	
Paula seriously blew the icicle between her pages.	nonsense	

Arthur bitterly remembered the river in the chicken.	nonsense	
Paula sleepily manipulated the mountain around the chef.	nonsense	
Nicole skilfully sharpened around the accent of the bread.	nonsense	
Chloe hastily kicked under the meadow roof.	nonsense	
Grace immediately rode the wish.	nonsense	
Hannah passively bounced over the hate.	nonsense	
Leah swiftly nodded the angle.	nonsense	
Ashley readily circled around the justice.	nonsense	
Claire politely crouched over the music.	nonsense	
Just idly hopped the new despair.	nonsense	
Lauren freely closed up the improvement.	nonsense	
Jason instantly bit into the education wit.	nonsense	
Tristan intensely chewed the large gossip after his shock.	nonsense	
Sonny rarely smashed the food in the sky.	nonsense	
Erin occasionally cut the mud in the bottle.	nonsense	
Nate reasonably emptied out the energy of the trust.	nonsense	

A2.2. Sentences Chapter 7

A2.2.1. Experiment 7-1

A2.2.1.1. Verb sentences

Sentence	**Target**	**Distractor**
The lion ambled/charged to the balloon	balloon	swing
The fox crawled/bolted to the rock	rock	tent
The clown dallied/hurried to the barrel	barrel	football
The boy dawdled/sprinted to the castle	castle	house
The deer meandered/dashed to the tree	tree	rock
The horse plodded/galloped to the flag	flag	wheelbarrow
The moose rambled/stormed to the hose	hose	ambulance
The gorilla roamed/sped to the lorry	lorry	barrel

The monkey sauntered/zipped to the pool	pool	bicycle
The elephant shuffled/raged to the present	present	bomb
The dog sneaked/shot to the shop	shop	bus
The man strolled/rushed to the tent	tent	car
The cat tiptoed/zoomed to the tree	tree	castle
The child traipsed/darted to the windmill	windmill	balloon
The girl trudged/raced to the circus	circus	flower
The bull wandered/ran to the bench	bench	mountain

A2.2.1.2 Adverb sentences

Sentence	**Target**	**Distractor**
The bear quickly/slowly advanced to the box	box	swing
The bull quickly/slowly bounded to the fence	fence	football
The cat quickly/slowly clambered to the buggy	buggy	sofa
The cow quickly/slowly coasted to the church	church	lorry
The deer quickly/slowly cruised to the palm tree	palm tree	pool
The dinosaur quickly/slowly fell to the bucket	bucket	cannon
The dog quickly/slowly hastened to the statue	statue	basket
The rabbit quickly/slowly hopped to the trolley	trolley	bench
The boy quickly/slowly jogged to the bottle	bottle	radio
The fox quickly/slowly jumped to the drum	drum	present
The horse quickly/slowly marched to the helicopter	helicopter	house
The chicken quickly/slowly moved to the snowman	snowman	broom
The goat quickly/slowly paced to the rocket	rocket	balloon
The gorilla quickly/slowly paraded to the broom	broom	anchor
The monkey quickly/slowly pranced to the lighthouse	lighthouse	flower
The pig quickly/slowly scampered to the rope	rope	house
The crocodile quickly/slowly shifted to the anchor	anchor	rock
The girl quickly/slowly skipped to the building	building	mountain

The snake quickly/slowly slid to the cannon	cannon	bucket
The elephant quickly/slowly stamped to the hot air balloon	balloon	barrel
The ostrich quickly/slowly strode to the motorcycle	motorcycle	flag
The chicken quickly/slowly strutted to the radio	radio	sofa
The duck quickly/slowly travelled to the robot	robot	shop
The donkey quickly/slowly trotted to the bus	bus	rope
The moose quickly/slowly walked to the cactus	cactus	bicycle

A2.2.1.3. Filler sentences

Sentence	Target	Distractor
The bear climbed to the mountain	mountain	bottle
The man hiked to the rock	rock	sofa
The donkey looked at the bomb	bomb	drum
The bird glanced at the castle	castle	hose
The gorilla studied the snowman	snowman	lighthouse
The cow noticed the robot	robot	motorcycle
The goat saw the garbage can	can	palm tree
The dinosaur watched the windmill	windmill	pool
The boy glowered at the car	car	radio
The man pointed at the tree	tree	wheelbarrow
The pig recognized the man	man	ambulance
The elephant surveyed the building	building	anchor
The dog growled at the football	football	bank
The clown scowled at the lion	lion	barrel
The rabbit viewed the tent	tent	basket
The duck visited the statue	statue	bench
The snake wanted the balloon	balloon	flag
The crocodile gazed at the canoe	canoe	lorry
The ostrich identified the helicopter	helicopter	radio
The chicken inspected the trolley	trolley	building

The bear observed the church	church	hose
The cat regarded the dog	dog	pool
The dinosaur scrutinized the rocket	rocket	present
The bird spotted the tree	tree	rope
The bull stared at the fence	fence	circus
The lion perceived the hot air balloon	balloon	swings
The cow ignored the buggy	buggy	flower
The fox encountered the ambulance	ambulance	radio
The monkey entered the bank	bank	drum
The moose approached the box	box	trolley
The clown called to the dog	dog	cactus
The boy patted the donkey	donkey	bomb
The man stroked the cat	cat	bin
The girl fed the chicken	chicken	shop
The child washed the elephant	elephant	sofa
The boy cleaned the horse	horse	broom
The girl cared for the goat	goat	castle
The child brushed the monkey	monkey	lighthouse
The clown comforted the girl	girl	balloon
The girl fondled the rabbit	rabbit	tent
The child caressed the bear	bear	windmill

A2.2.2. Experiment 7-2

A2.2.2.1. Additional verb sentences

Sentence	**Target**
The fox ambled/charged to the bench	bench
The clown crawled/bolted to the balloon	balloon
The boy dallied/hurried to the rock	rock
The deer dawdled/sprinted to the barrel	barrel
The horse meandered/dashed to the castle	castle
The moose plodded/galloped to the tree	tree

The gorilla rambled/stormed to the flag	flag
The monkey roamed/sped to the hose	hose
The elephant sauntered/zipped to the lorry	lorry
The dog shuffled/raged to the pool	pool
The man sneaked/shot to the present	present
The cat strolled/rushed to the shop	shop
The child tiptoed/zoomed to the tent	tent
The girl traipsed/darted to the tree	tree
The bull trudged/raced to the windmill	windmill
The lion wandered/ran to the circus	circus

A2.2.3. Experiment 7-3

A2.2.3.1.Verb sentences

Sentence	**Target**	**Distractor**
The bull crawled/charged to the circus	circus	mountain
The lion dallied/bolted to the bench	bench	swings
The fox dawdled/hurried to the balloon	balloon	teepee
The clown meandered/sprinted to the rock	rock	football
The boy plodded/dashed to the barrel	barrel	house
The deer rambled/galloped to the castle	castle	rock
The horse roamed/stormed to the tree	tree	wheelbarrow
The moose sauntered/sped to the flag	flag	ambulance
The gorilla shuffled/zipped to the hose	hose	barrel
The monkey sneaked/raged to the lorry	lorry	bike
The elephant strolled/shot to the pool	pool	bomb
The dog tiptoed/rushed to the present	present	bus
The man traipsed/zoomed to the shop	shop	car
The cat trudged/darted to the tent	tent	castle
The child wandered/raced to the tree	tree	balloon
The girl ambled/ran to the windmill	windmill	flower

A2.2.3.2. Filler sentences

Sentence	Target	Distractor
The bear climbed to the mountain	mountain	-
The man hiked to the rock	rock	sofa
The donkey looked at the bomb	bomb	-
The bird glanced at the castle	castle	hose
The gorilla studied the snowman	snowman	-
The cow noticed the robot	robot	bike
The goat saw the garbage can	garbage can	-
The dinosaur watched the windmill	windmill	pool
The boy glowered at the car	car	-
The man pointed at the tree	tree	wheelbarrow
The pig recognized the man	man	-
The elephant surveyed the building	building	anchor
The dog growled at the football	football	-
The clown scowled at the lion	lion	bear
The rabbit viewed the tent	tent	-
The duck visited the statue	statue	shop
The snake wanted the balloon	balloon	-
The crocodile gazed at the canoe	canoe	anchor
The ostrich identified the helicopter	helicopter	-
The chicken inspected the trolley	trolley	bin
The bear observed the church	church	-
The cat regarded the dog	dog	rabbit
The dinosaur scrutinized the rocket	rocket	-
The bird spotted the tree	tree	rock
The bull stared at the fence	fence	-
The lion perceived the hot air balloon	balloon	tent
The cow ignored the buggy	buggy	-
The fox encountered the ambulance	ambulance	lorry
The monkey entered the bank	bank	-

The moose approached the box	box	tree
The clown called to the dog	dog	-
The boy patted the donkey	donkey	rabbit

A2.2.4. Experiment 7-4
A2.2.4.1. Adverb sentences

Sentence	Target
The lion calmly/abruptly went to the rock	rock
The fox carefully/actively went to the barrel	barrel
The clown casually/briskly went to the castle	castle
The boy cautiously/frantically went to the tree	tree
The deer gently/hastily went to the flag	flag
The horse gradually/hurriedly went to the hose	hose
The moose idly/immediately went to the lorry	lorry
The gorilla lazily/promptly went to the pool	pool
The monkey leisurely/quickly went to the present	present
The elephant listlessly/rapidly went to the shop	shop
The dog reluctantly/readily went to the tent	tent
The man sleepily/speedily went to the tree	tree
The cat slowly/suddenly went to the windmill	windmill
The child sluggishly/swiftly went to the circus	circus

A2.2.4.2. Fillers

Sentence	Target
The monkey climbed to the mountain	mountain
The boy hiked to the rock	rock
The bird looked at the bomb	bomb
The gorilla glanced at the castle	castle
The cow studied the snowman	snowman
The goat noticed the robot	robot
The dinosaur saw the garbage can	garbage can

The boy watched the windmill	windmill
The man glowered at the car	car
The girl pointed at the tree	tree
The elephant recognized the girl	girl
The dog surveyed the church	church
The clown smiled at the boy	boy
The rabbit hid from the lion	lion
The duck viewed the tent	tent
The snake visited the statue	statue
The crocodile wanted the balloon	balloon
The ostrich gazed at the canoe	canoe
The chicken identified the helicopter	helicopter
The bear inspected the shop	shop
The cat observed the building	building
The dinosaur regarded the dog	dog
The bird scrutinized the rocket	rocket
The bull spotted the tree	tree
The lion stared at the dog	dog
The cow perceived the hot air balloon	balloon
The fox ignored the bear	bear
The monkey encountered the snake	snake

Appendix 3 Additional analyses Chapter 7

A3.1 Mouse response times Experiment 7-1

Mouse response times to the correct target destination were calculated from the onset of the final noun. For verb sentences a 2 (speaking rate) X 2 (verb speed) repeated measures ANOVA found a main effect of speaking rate (*F1* (1, 39) = 13.07, $p <$ .001, η^2_p = .25; *F2* (1, 15 = 4.77, p = .045, η^2_p = .24), with click times faster to sentences spoken slowly compared to sentences spoken quickly. There was no main effect of verb type (*F*s < 1) and no interaction (*F*s < 1).

For adverbs sentences a 2 (speaking rate) X 2 (verb speed) repeated measures ANOVA also found a significant effect of speaking rate (*F1* = 37.19, $p <$ .001, η^2_p = .49; *F2* (1, 24) = 12.76, p = .002, η^2_p= .35) with click times faster to sentences spoken slowly compared to sentences spoken quickly. There was no main effect of adverb speed and no interaction (*F*s < 1).

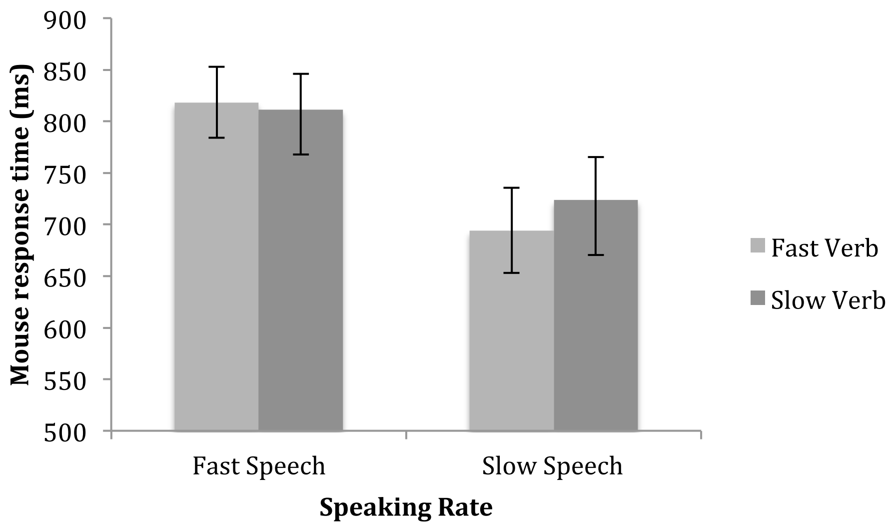

Figure A3-1. Average mouse response time for verb sentences in Experiment 7-1. Error bars reflect 1 standard error.

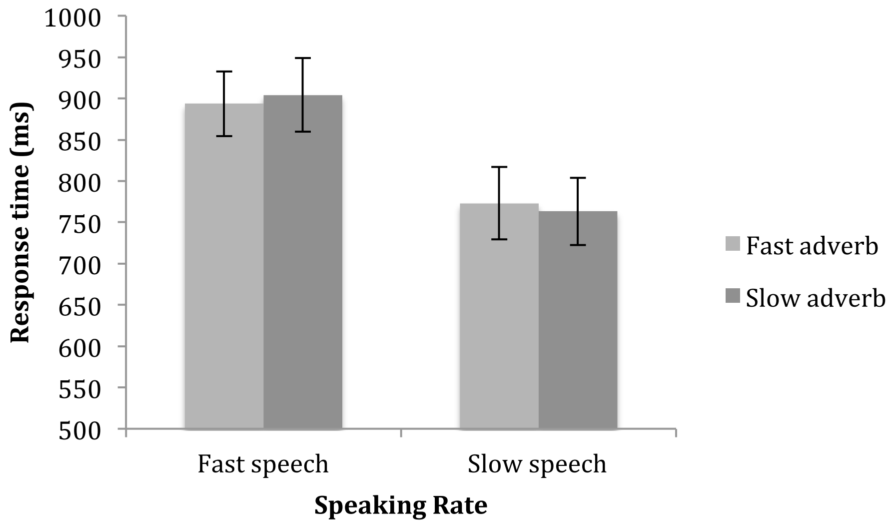

Figure A3-2. Average mouse response time for adverb sentences in Experiment 7-1. Error bars reflect 1 standard error.

A3.2. Comprehension questions Experiment 7-2

Accuracy and response times (for correct responses) were recorded for comprehension questions that were not preceded by a verb judgment only (because the verb task might have somehow interfered with the current representation of the sentence meaning). Responses less that 300ms and outside 2.5*SD* of a participant's average response time were removed.

A3.2.1. Accuracy

For verb sentences, a 2 (speaking rate) X 2 (verb speed) ANOVA on the arcsine transformed accuracy responses found no main effect of speaking rate (Fs < 1) and no interaction ($F1$ (1, 51) = 1.79, p = .19, η^2_p = .034; $F2$ < 1). There was a marginal effect of verb type by subjects and significant effect by items ($F1$ (1, 51) = 3.48, p = .068, η^2_p = .064; $F2$ (1, 28) = 5.69, p = .024, η^2_p = .17), with responses to comprehension questions being less accurate for slow verb sentences than fast verbs sentences, particularly in the fast speaking rate condition. This may reflect interference between speed of the verb (slow) and speaking rate of the sentence (fast), which subsequently hindered comprehension.

For adverb sentences a 2 (adverb speed) X 2 (speaking rate) ANOVA on the arcsine transformed accuracy responses found no effect of adverb speed, no effect of speaking rate and no interaction (*F*s < 1).

A3.2.2. Response time

For verb sentences, one participant had an empty cell due to trials being removed because they were incorrect or outside 2.5*SD*s of their mean response time. I therefore replaced the cell with the overall average response time to keep an equal *n* in the analysis

Looking at response times for verb sentences for correct responses only, a 2 (verb speed) X 2 (speaking rate) ANOVA found a marginal effect of speaking rate ($F1$ (1, 51) = 2.1, p = .15, η^2_p = .039; $F2$ (1 28) = 3.66, p = .066, η^2_p = .12) with responses slower following slow speaking rate. There was no main effect of verb speed ($F1$ (1, 51) = 1.56, p = .22, η^2_p = .03; $F2$ (1, 28) = 2.86, p = .1, η^2_p = .093) and no significant interaction ($F1$ <1; $F2$ (1, 28) 1.02, p = .32, η^2_p = .035)).

Looking at response times for adverb sentences for correct responses only, a 2 (verb speed) X 2 (speaking rate) ANOVA found no effect of speaking rate (Fs <1), no main effect of verb speed (*F*s) and no significant interaction ($F1$ (1, 51) = 1.54, p = .22, η^2_p = .029; $F2$ (1, 28) 1.02, p = .32, η^2_p = .035)).

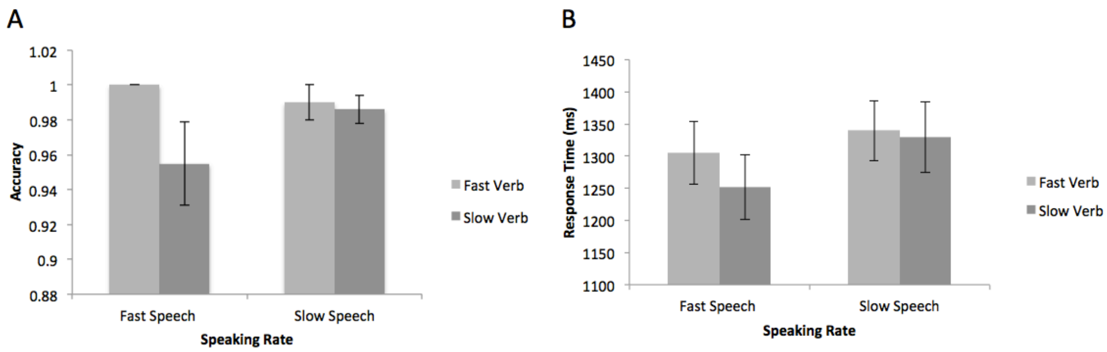

Figure A3-3. Average accuracy (A) and response time (B) to comprehension questions for verb sentences in Experiment 7-2. Error bars reflect 1 standard error.

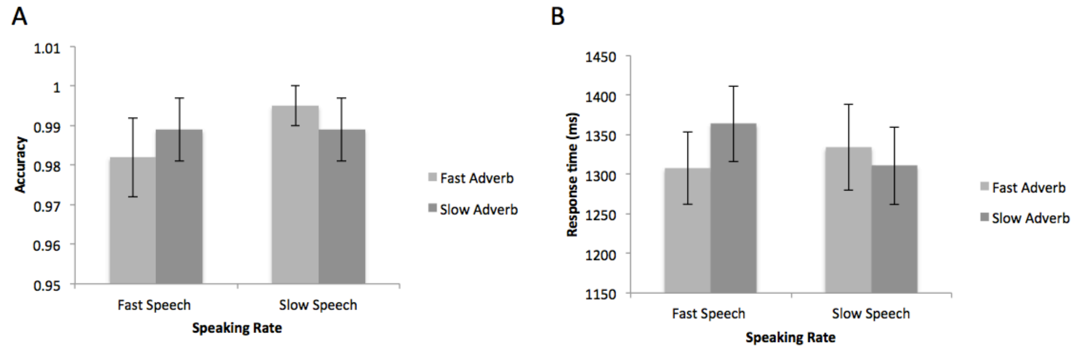

Figure A3-4. Average accuracy (A) and response time (B) to comprehension questions for adverb sentences in Experiment 7-2. Error bars reflect 1 standard error.

A3.3. Comprehension questions Experiment 7-3

Accuracy and response time to comprehension questions was recorded. Responses outside 2.5*SD* of a participant's mean response time were removed.

A3.3.1. Accuracy

A 2 (verb speed) X 2 (scene type) ANOVA on the arcsine transformed accuracy responses found no main effect of verb by subjects ($F1$ (1, 39) = 12.32, p = .14, η^2_p = .056) but a significant effect by items ($F2$ (1, 15) = 11.85, p = .004, η^2_p = .44), such that responses were less accurate to sentence with fast verbs. This result is not predicted and there is no obvious explanation for why participants would be less accurate to fast verb sentences here but not in the previous two experiments. There was a main effect of scene type (F1 (1, 39) = 12.31, p< .011, η^2_p = .24; *F2* (1, 15) = 11.93, *p* = .004, η^2_p = .44). Accuracy was lower for scenes with a distractor than for scenes without a distractor. This is an interesting result in terms of the dwell time data, suggesting that comprehension is hindered when the scene is ambiguous and simulation is reduced. Comprehension differences cannot be attributed to differences in properties of the sentences, since exactly the same sentences were used for both scene types, but rather they are more likely due to the setup of the visual scene. Since comprehension scores were not a fundamental aspect of the investigation and were instead included to ensure participants fully attended to the sentences they were therefore not carefully designed and controlled thus strong conclusions about the results cannot be drawn. They do however raise an interesting question that should be further pursued: if a simulation is manipulated in some way, does this affect comprehension? Finally, there was no interaction between verb and scene type (Fs<1).

A3.3.2. Response time

For response time, one subject had two blank cells due to trials being removed because they were incorrect or outside of 2.5*SD*s of their mean response time. I therefore replaced these cells with the participant's mean response time to keep an equal *n*. There was no effect of verb speed (*F*s<1), scene type (*F*s<1) and no interaction between them by subjects (*F1* (1, 39) = 2.47, *p* = .12, η^2_p = .059) but a marginal interaction by items (*F2* (1, 15) = 4.34, *p* = .055, η^2_p = .22) such that responses were slower to comprehension questions following fast verb sentences in scenes with a distractor, with the opposite pattern for scenes without a distractor. Since this effect was only marginally significant by items and was not predicted by any of the hypotheses in this chapter, it would need to be further investigated.

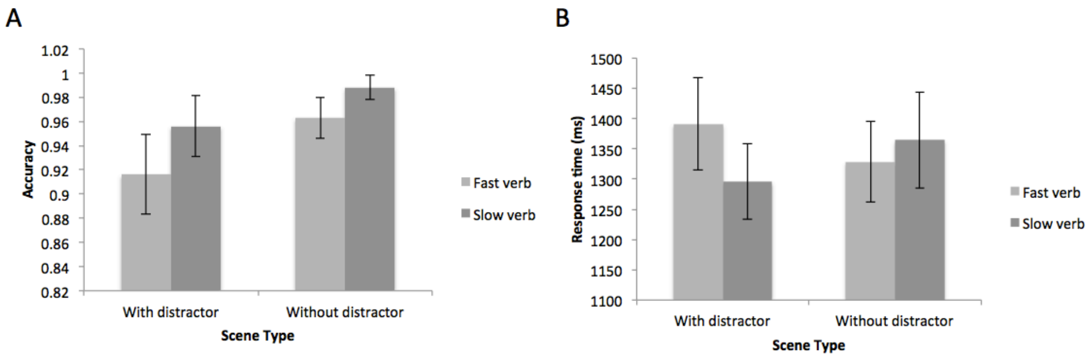

Figure A3-5. Average accuracy (A) and response time (B) to comprehension questions in Experiment 7-3. Error bars reflect 1 standard error.

A3.4. Comprehension questions Experiment 7-4

Accuracy and response time to comprehension questions was recorded. Responses outside 2.5*SD* of a participant's mean response time were removed.

A3.4.1. Accuracy

A 2 (adverb speed) X 2 (speaking rate) ANOVA found a marginal effect of speaking rate (*F1* (1, 43) = 3.96, p = .053, η^2_p = .084; *F2* (1, 13) = 2.77, p = .12, η^2_p = .18) such that responses were more accurate with slow speaking rate. This supports the idea that comprehension is hindered when sentences are spoken quickly. There was also a marginal interaction (*F1* (1, 43) = 2.96, p = .093, η^2_p = .064; *F2* (1, 13) = 2.8, p = .12, η^2_p = .18) with a trend for responses to be more accurate when the speed of adverb and the speaking rate matched compared to when they did not match. There was no effect of adverb speed (*F*s< 1).

A3.4.2. Response time

For response time, one subject had an empty cell due to too many incorrect response or trials being removed for being outside 2.5*SD* of the average response time. I therefore replaced that cell with their average response time.

A 2 (adverb speed) X 2 (speaking rate) ANOVA found a main effect of speaking rate (*F1* (1, 43) = 4.67, p = .036, η^2_p = .098; *F2* (1, 13) = 4.02, p = .066, η^2_p = .24) such that responses were slower following slow speaking rate. There was a marginal effect of adverb speed by items but not subjects (*F1* < 1; *F2* (1, 13) = 3.8, p = .073, η^2_p = .23) with responses slower to sentences with slow adverbs compared to fast adverbs, and no interaction (*F1* <1; *F2* (1, 13) = 1.96, p = .19, η^2_p = .13).

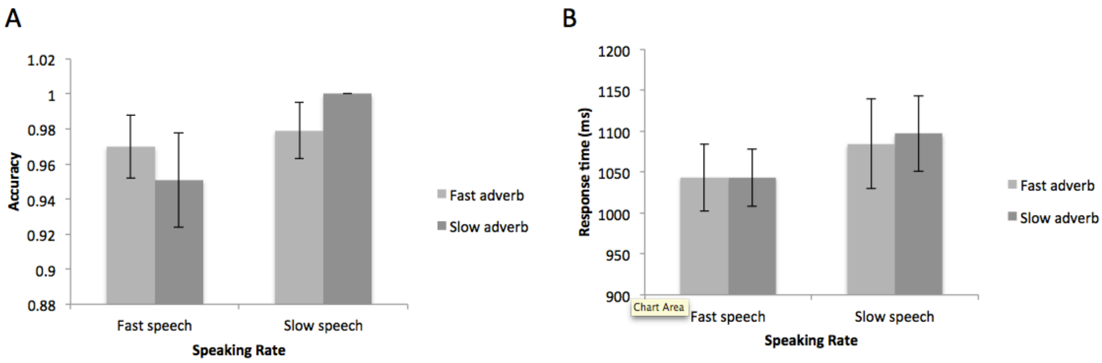

Figure A3-6. Average accuracy (A) and response time (B) to comprehension questions in Experiment 7-4. Error bars reflect 1 standard error.

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